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ANALYTICAL EVALUATION OF EFFECT OF EQUIVALENCE RATIO
INLET-AIR TEMPERATURE, AND COMBUSTION PRESSURE
ON PERFORMANCE OF SEVERAL POSSIBLE
RAM-JET FUELS

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

September 14, 1953

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUMANALYTICAL EVALUATION OF EFFECT OF EQUIVALENCE RATIO, INLET-AIR
TEMPERATURE, AND COMBUSTION PRESSURE ON PERFORMANCE
OF SEVERAL POSSIBLE RAM-JET FUELS

By Leonard K. Tower and Benson E. Gammon

SUMMARY

An analytical investigation conducted to determine the theoretical air specific impulse performance of several fuels over a range of equivalence ratios, inlet-air temperatures, and combustion pressures is reported herein. The fuels include octene-1, 50-percent-magnesium slurry, boron, pentaborane, diborane, hydrogen, carbon, and aluminum. Inlet-air temperatures between 100° and 900° F are considered at a combustion pressure of 2 atmospheres; a combustion pressure of 0.2 atmosphere is also considered at an inlet-air temperature of 100° F.

The benefit to air specific impulse of an increase in inlet-air temperature at the higher equivalence ratios was reduced by such high temperature effects as dissociation and increased specific heats of the combustion products. An increase in combustion pressure from 0.2 to 2 atmospheres raised the air specific impulse level as much as 5 seconds at higher equivalence ratios. The fuel consumption of pentaborane and diborane remained below that of octene-1 despite the adverse effect of boron oxide vaporization on the performance of fuels containing boron at combustion temperatures exceeding 3000° R; the fuel consumption of boron became higher than that of octene-1 above this temperature. Boron, as well as diborane and pentaborane, provided higher air specific impulse than octene-1 at an equivalence ratio of 1.0.

Means are shown for extending the data to inlet conditions beyond the limited range of inlet-air temperatures and combustion pressures considered. Also discussed are the determination of air specific impulse efficiency and combustion efficiency for experimental data by the use of theoretical results and the estimation of the relative amounts of the various fuels required to maintain a fixed level of thrust in an engine.

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INTRODUCTION

The ever increasing performance required of high-speed aircraft places new demands upon the propulsion system. Improved range, thrust, combustion efficiency, and combustion stability characteristics may possibly be obtained by the use of the high-energy jet-engine fuels. These materials promise advantages over conventional hydrocarbon fuels because of their higher heating value on a gravimetric or volumetric basis, or because of the ease and stability of their combustion. Currently designated among the high-energy jet-engine fuels are certain of the light elements such as boron, aluminum, and magnesium, alloys and hydrides of these elements, and paintlike suspensions of the solid materials in a liquid hydrocarbon (slurries). Considerable experimental work, summarized in reference 1, has been conducted with certain high-energy fuels to determine their suitability for selected applications in aircraft. The NACA Lewis laboratory has determined some of the physical properties and combustion properties of diborane, boron, magnesium, and aluminum, the metals having been burned in the form of powder, wire, and slurries (refs. 1 to 5).

The theoretical performance of high-energy ram-jet fuels is of interest both in evaluating experimental results and in judging the potentialities of proposed but untested materials. Theoretical comparisons of fuels burned in a great excess of cool air may be based upon heating values per pound of fuel, per pound of air, or per cubic foot of fuel. When the temperatures obtained in the combustion process become very high, however, considerable energy is absorbed by dissociation, vaporization, fusion, and increases in specific heats of the combustion products. The performance of fuels at elevated temperatures is thus determined both by the heating value of the fuel and by the thermal properties of its combustion products. Thus the theoretical performance of a fuel must be determined by an analytical method which can account for as many thermal effects as possible.

By means of such an analytical method, the theoretical performance of many high-energy jet-engine fuels has been studied at a single combustor inlet-air temperature of 100° F and at a combustion pressure of 2 atmospheres (ref. 6). These data can be compared with experimental data at the same conditions to evaluate the combustion test performance of an engine. In practice, of course, few cases will be encountered where an engine is operating precisely at an inlet temperature of 100° F and a combustion pressure of 2 atmospheres.

The present report extends the theoretical data of reference 6 for several fuels to other combustion pressures and inlet-air temperatures and thus facilitates the evaluation of experimental data. The fuels

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considered herein include octene-1, slurry of 50-percent magnesium in octene-1, boron, pentaborane, diborane, hydrogen, carbon, and aluminum. Some examples are given of the manner in which this theoretical information can be used in the operation of engines and in the evaluation of experimental data.

SYMBOLS

The following symbols are used in this report:

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- A area, sq ft
- F stream thrust, lb
- F_n net internal thrust, lb
- g acceleration due to gravity, 32.17 ft/sec^2
- (H_T^0) sum of the sensible enthalpy and chemical energy at temperature T and at standard conditions, kcal/mole
- M Mach number
- m molecular weight of a constituent
- \bar{m} mean molecular weight
- n number of moles of a constituent
- p static pressure, lb/sq ft
- R universal gas constant, $\text{ft-lb}/(\text{lb})(^0\text{R})$
- s_a air specific impulse, lb-sec/lb air
- $s_{f,w}$ fuel-weight specific impulse, lb-sec/lb fuel
- T total temperature, ^0R
- t static temperature, ^0R
- v velocity, ft/sec
- w weight flow, lb/sec
- x weight fraction of solids in exhaust gases

γ ratio of specific heats

η efficiency

η_{S_a} air specific impulse efficiency

Φ equivalence ratio; ratio of actual to stoichiometric fuel-air ratio

$\varphi(M)$ stream-thrust correction factor to $M = 1$

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Subscripts:

a air

c combustion, combustor outlet

cr crystal

e exhaust-nozzle outlet

exp experimental

f fuel

g gas

i denotes i^{th} constituent of combustion products

in engine inlet

l liquid

s solid

t theoretical

w weight

Superscript:

* denotes a station having a Mach number of unity

ANALYTICAL METHOD

Suitable thrust parameters for both theoretical and actual jet-engine fuel performance have been found to be air specific impulse and

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fuel specific impulse, or total stream momentum per pound of air and per pound of fuel, respectively. Air specific impulse is defined as

$$S_a = \frac{1}{w_a} \left(pA + \frac{wV}{g} \right)^* \quad (1)$$

where

$$w = w_a + w_f$$

and fuel-weight specific impulse is defined as

$$S_{f,w} = \frac{1}{w_f} \left(pA + \frac{wV}{g} \right)^* = \frac{S_a}{w_f/w_a} \quad (2)$$

Air specific impulse can also be expressed as

$$S_a = \left(1 + \frac{w_f}{w_a} \right) \sqrt{\frac{2(\bar{\gamma}+1) RT_c}{\bar{\gamma} g \bar{m}}} \quad (3)$$

where $\bar{\gamma}$ is an effective ratio of specific heats. The net internal thrust of an engine can be determined simply from the relation

$$F_n = \frac{w_a S_a}{\varphi(M_e)} - \left(pA + \frac{wV}{g} \right)_{in} \quad (4)$$

(see ref. 6), where $\varphi(M)$ is a function relating stream thrust at any station to stream thrust at a station having a Mach number of unity. (See eqs. (A2) and (A3) of the appendix.) The significance and the utility of these concepts are discussed in more detail in reference 7.

The theoretical determination of air specific impulse and fuel specific impulse for the fuels considered herein involved two principal steps: (1) The combustion temperature and burned-product composition were determined at the assigned combustion pressure, and (2) an isentropic expansion in the exhaust nozzle over an expansion ratio of 2:1 determined the exhaust-nozzle-outlet static temperature and velocity. The results of step (2) were used to compute air and fuel specific impulse.

The method of computing combustion temperature and composition was that of reference 8. A set of simultaneous equations was solved which involved mass balance, heat balance, pressure, phase changes, and dissociation of solid, liquid, and gaseous molecules. The necessary thermodynamic properties of almost all the dissociated and undissociated combustion products were taken from tables included in reference 8. An empirical equation given in reference 9 for the specific heat of magnesium oxide was used to obtain tabulated values of specific heat, enthalpy, and entropy for magnesium oxide; the standard state entropy of magnesium oxide was taken from reference 10.

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Thermal properties which were required in setting up the equation of heat balance for the fuels considered herein are presented in table I. Shown in table I is either the heat of formation, or the heat of combustion, or both for each fuel. By means of the heat of formation or the related heat of combustion, an assigned enthalpy, presented in table I, was computed for each fuel. This enthalpy was consistent with the arbitrary base of reference 8. Because of their arbitrary bases, the enthalpies assigned to the fuels give no indication of the heat liberated in combustion.

The following assumptions were made concerning the combustion process in order to simplify the analysis: (1) All fuels were pure; (2) air was composed of 3.78 moles of nitrogen to every mole of oxygen; (3) combustion inlet-air velocity was negligible so that the combustion static temperature and the combustion total temperature were equal; (4) all gases were ideal; and (5) combustion was adiabatic and complete, that is, chemical equilibrium was assumed. When solids or liquids were present in the combustion products, the volume occupied by the condensed material was negligible, and thermal and velocity equilibrium existed between the different phases.

The products of adiabatic combustion of each fuel which were considered possible in the computations of composition are listed in table II. They were gaseous except as noted. The possible formation of nitrides of boron, magnesium, and aluminum was neglected because of inadequate thermodynamic data. For the same reason, dissociation, fusion, and vaporization of magnesium oxide were neglected.

The exhaust-nozzle-outlet temperature was determined by computing an isentropic expansion from the combustion temperature and pressure over a pressure ratio of 2:1. It was assumed that in the nozzle (1) composition was fixed during the expansion process, (2) the volume occupied by condensed materials was negligible, and (3) condensed materials were in thermal and velocity equilibrium with the gas phase. The jet velocity was then calculated by using the following equation (ref. 11):

$$\frac{V_e}{g} = 294.98 \sqrt{\left(\frac{\sum n_i (H_T^0)_i}{\sum n_i m_i}\right)_c - \left(\frac{\sum n_i (H_T^0)_i}{\sum n_i m_i}\right)_e} \quad (5)$$

The air specific impulse was then

$$s_a = \left(1 + \frac{w_f}{w_a}\right) \left[\frac{V_e}{g} + \frac{R t_e}{m_g V_e} (1 - x) \right] \quad (6)$$

The jet velocity V_e , determined for an expansion ratio of 2:1 in the exhaust nozzle, covered a range of Mach numbers near unity. The error introduced into the air specific impulse function by assuming a Mach number of 1 for V_e , determined thus, was 0.5 percent or less (ref. 12). The air specific impulse was not corrected for this error.

PRESENTATION OF DATA

The effects of combustor inlet conditions upon the theoretical combustion performance of the fuels are shown in figures 1 to 8. The figures pertain to the fuels as follows:

Octene-1 (liq.)	1
Slurry of 50-percent magnesium in octene-1	2
Carbon (graphite)	3
Boron (cryst.)	4
Pentaborane (liq.)	5
Diborane (liq.)	6
Hydrogen (liq.)	7
Aluminum (cryst.)	8

The effect of inlet-air temperature and equivalence ratio or fuel-air ratio upon combustion performance at a combustion pressure of 2 atmospheres is shown in parts (a), (b), and (c) of each figure. Equivalence ratios of 0.1 to 1.0 and inlet-air temperatures of 100°, 500°, and 900° F are considered. For aluminum, data are shown only for inlet-air temperatures of 100° and 500° F.

The variation of combustion temperature with inlet-air temperature and equivalence ratio is presented in parts (a); the variation of air specific impulse with inlet-air temperature and equivalence ratio is presented in parts (b), and the variation of the reciprocal of fuel-weight specific impulse with air specific impulse and inlet-air temperature is presented in parts (c). Also shown on parts (c) are lines of constant fuel-air ratio. Reciprocal fuel-weight specific impulse has been used instead of fuel-weight specific impulse to improve readability of the curves. These parts (c) of the figures may be employed to compare the performance of different fuels at the same inlet conditions

as explained in the section Determination of relative fuel-flow requirements for given engine. Parts (c) cannot be used to compare the theoretical performance of a fuel at one inlet condition with the performance of the same fuel at another inlet condition, since changes in inlet-air temperature are obtained in the free-flying ram jet only by change in altitude or flight Mach number. The net thrust of the engine is then no longer determined by the air specific impulse alone, but is also affected by the changing inlet condition (eq. (4)).

The effect of combustion pressure and equivalence ratio on the air specific impulse of each fuel except aluminum is presented in parts (d) and (e) of each figure. Equivalence ratios ranging from 0.7 to 1.0 and combustion pressures of 0.2 and 2 atmospheres are considered at an inlet-air temperature of 100° F. In parts (d), the variation of air specific impulse with equivalence ratio is presented at the two combustion pressures, and, in parts (e), air specific impulse is presented against the logarithm of combustion pressure at four equivalence ratios. Figure parts (e) are useful in adjusting theoretical air specific impulse determined for any inlet-air temperature to any desired combustion pressure, as discussed in the section Determination of air specific impulse at combustor inlet conditions other than those reported.

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ANALYSIS OF DATA

Octene-1, 50-percent-magnesium slurry, and carbon. - Figures 1(a), 2(a), and 3(a) for octene-1, 50-percent-magnesium slurry, and carbon, respectively, show that a given increase in inlet-air temperature results in a diminishing gain in combustion temperature as equivalence ratio is raised. For example, the combustion temperature of octene-1 (fig. 1(a)) at an equivalence ratio of 0.1 is increased 745° R by raising the inlet-air temperature from 100° to 900° F, while at an equivalence ratio of 1.0, the same increase in inlet-air temperature raises the combustion temperatures only 320° R. The elevated combustion temperatures occurring at the higher equivalence ratios result in increased specific heats and more dissociation of combustion products. Much of the heat made available by an increase in inlet-air temperature is thereby absorbed without a corresponding gain in combustion temperature.

Since air specific impulse is a function of combustion temperature (eq. (3)), the gain in air specific impulse achieved by a given increase in inlet-air temperature becomes less when equivalence ratio is raised, as shown in figures 1(b), 2(b), and 3(b). Raising the inlet-air temperature from 100° to 900° F increased the air specific impulse of octene-1 by 24.6 seconds at an equivalence ratio of 0.1, but only by 7.3 seconds at an equivalence ratio of 1.0 (fig. 1(b)).

In figures 1(d), 2(d), and 3(d), it is shown that the air specific impulse at a combustion pressure of 0.2 atmosphere is less than that at a combustion pressure of 2 atmospheres within the range of equivalence ratios shown (0.7 to 1.0). Moreover, the loss in air specific impulse with this decrease in combustion pressure is greatest at the richer equivalence ratios. A decrease in combustion pressure shifts the chemical equilibrium among all the combustion products toward the condition of more dissociation. The resulting absorption of thermal energy lowers the air specific impulse. Since dissociation becomes greater at the higher combustion temperatures associated with richer equivalence ratios, the loss in air specific impulse with lowered combustion pressures becomes more serious as equivalence ratio is raised.

Although the data of figures 1(e), 2(e), and 3(e) were computed for only two combustion pressures, a straight line of air specific impulse against the logarithm of combustion pressure for each equivalence ratio has been drawn between combustion pressures of 0.2 and 2 atmospheres. For fixed expansion ratios and equivalence ratios, the theoretical impulse V_e/g of a rocket varies very nearly linearly with the logarithm of chamber pressure as shown in reference 13. This semilogarithmic relation is extended herein to ram-jet air specific impulse against combustion pressure. As a verification, air specific impulse at an equivalence ratio of 1.0 was computed for octene-1 at two additional combustion pressures of 0.6 and 10 atmospheres. These data are represented on figure 1(e) by the circled points. This semilogarithmic relation between air specific impulse and combustion pressure is expected to be valid for all eight fuels reported here at equivalence ratios from 0.7 to 1.0. Extrapolation of the lines from 2 to 10 atmospheres combustion pressure is less satisfactory than interpolation between 0.2 and 2 atmospheres. All lines have therefore been shown broken above 2 atmospheres.

Boron, pentaborane, diborane, and hydrogen. - These fuels comprise a sequence in which boron is combined with increasing percentages of hydrogen. One of the combustion products, boron oxide, vaporizes between 3000° and 3500° R, with a loss in air specific impulse resulting from heat absorption. In the following table are shown the mole fractions of boron and hydrogen in the fuels and the approximate heat absorbed by vaporizing the boron oxide formed from a pound of each fuel. Also shown is the approximate heat absorbed by vaporizing the boron oxide formed from a pound of stoichiometric fuel-air mixture. For convenience, these heats of vaporization have been evaluated at a temperature of 3240° R.

Fuel	Mole fraction of constituents		Heat absorbed by vaporization of boron oxide	
	Boron	Hydrogen	Btu/lb fuel	Btu/lb stoichio-metric fuel-air mixture
Boron	1.0	0	5314	503
Pentaborane	.357	.643	4551	323
Diborane	.250	.750	4153	261
Hydrogen	0	1.00	0	0

As the amount of boron in the fuel decreases, the heat absorbed by vaporization of boron oxide also decreases.

Comparison of figures 4(a), 5(a), and 6(a) shows irregularities in the curves of combustion temperature against equivalence ratio, beginning at about 3000° R, caused by vaporization of the boron oxide. The irregularities become progressively less severe as the hydrogen content of the fuel is raised, because of the decreasing amount of heat absorbed by vaporization of boron oxide. The effect of this vaporization on the thrust performance of the fuels is shown in figures 4(b), 5(b), and 6(b) (variation of air specific impulse with equivalence ratio and inlet-air temperature) and in figures 4(c), 5(c), and 6(c) (variation of reciprocal fuel-weight specific impulse with air specific impulse and inlet-air temperature). It is of interest to compare the reciprocal fuel-weight specific impulse (fuel consumption) of these fuels with that of octene-1 (fig. 1(c)) at levels of air specific impulse below and above the vaporization region of boron oxide. For levels of air specific impulse less than 140 seconds and at any inlet-air temperature, a higher reciprocal fuel-weight specific impulse (greater fuel consumption) is experienced with octene-1 than with boron, pentaborane, or diborane. At air specific impulses exceeding 140 seconds, octene-1 actually shows a lower fuel-weight specific impulse (less fuel consumption) than boron, for any inlet-air temperature. While the reciprocal fuel-weight specific impulses of both pentaborane and diborane rise sharply at an air specific impulse of about 140 seconds, their fuel consumption remains lower than that of octene-1 at all levels of air specific impulse. At an equivalence ratio of 1.0, boron, as well as diborane and pentaborane, provides a higher air specific impulse than octene-1 (figs. 4(b), 5(b), and 6(b)).

It is shown in figure 4(d) that the air specific impulse of boron at an equivalence ratio of 1.0 is raised 5 seconds by increasing the combustion pressure from 0.2 to 2.0 atmospheres. This, the largest gain experienced by any of the fuels considered herein, results from suppressing the dissociation made possible by the high combustion temperature of boron.

Liquid hydrogen has by far the lowest reciprocal fuel-weight specific impulse (lowest fuel consumption) of any of the fuels considered herein, at any level of air specific impulse (fig. 7(b)). Despite its outstanding combustion properties, liquid hydrogen does not appear promising as a ram-jet fuel because of its low liquid density (ref. 6) and difficulties of handling and storage.

Aluminum. - Aluminum produces an oxide which vaporizes at elevated temperatures. This vaporization has an adverse effect on the combustion performance of aluminum, as the irregularities in the curves of figures 8(a) to (c) indicate.

APPLICATIONS OF DATA

Determination of air specific impulse at combustor inlet conditions other than those reported. - In many instances it is desired to know the air specific impulse at inlet conditions other than those for which the data of figures 1 to 8 were computed. Approximate values of air specific impulse at other inlet conditions may be determined as follows:

At the lower equivalence ratios (below 0.7) the effect of pressure is usually negligible. The air specific impulse at these lower equivalence ratios can be read directly from the curves of air specific impulse against equivalence ratio and inlet-air temperature (parts (b) of the figures) without consideration of combustion pressure. An exception to this arises with materials containing boron, where the vaporization of boron oxide in the vicinity of an equivalence ratio of 0.4 is pressure dependent. A direct computation is then necessary.

At equivalence ratios exceeding 0.7, the effect of combustion pressure upon air specific impulse becomes important for all fuels. The effect of combustion pressure on air specific impulse in this region can be determined in the following manner: The air specific impulse at the desired inlet-air temperature, determined from parts (b) of the figures, is entered in parts (e) at a pressure of 2 atmospheres. The air specific impulse is then corrected to the desired pressure along a line of constant composition (constant equivalence ratio). For example, the air

specific impulse of boron at an equivalence ratio of 0.8, an inlet-air temperature of 800° F, and a combustion pressure of 0.3 atmosphere can be found as follows: From figure 4(b) the air specific impulse is determined as 182.6 seconds for the conditions stated, but at a combustion pressure of 2 atmospheres. The value obtained is entered in figure 4(e) at this pressure and air specific impulse (point A), and a line of constant composition is followed to a pressure of 0.3 atmosphere (point B). The desired air specific impulse is found to be 178.8 seconds. This is very close to the value of 178.83 seconds determined by direct computation for a pressure of 0.3 atmosphere.

In making a pressure correction, it may be necessary occasionally to enter data in a figure such as 4(e) at an air specific impulse exceeding the highest line of air specific impulse against combustion pressure. For example, figure 4(b) indicates an air specific impulse of 190.5 seconds for an equivalence ratio of 1.0, an inlet-air temperature of 900° F, and a combustion pressure of 2 atmospheres. A point C is thus located on figure 4(e) which is above the highest line already present. A correction to a combustion pressure of 0.2 atmosphere, made along a dashed line converging toward existing lines at the same rate with which they converge toward each other, locates an air specific impulse of 184.6 seconds at point D. By direct computation, the value sought is found to be 184.7 seconds.

Determination of air specific impulse efficiency and combustion efficiency. - Both air specific impulse efficiency and combustion efficiency may be found for experimental data by the use of curves presented herein. Air specific impulse efficiency is defined as the ratio of the experimental air specific impulse to the theoretical air specific impulse at the same equivalence ratio:

$$\eta_{S_a} = \left(\frac{S_{a, \text{exp}}}{S_{a, t}} \right)_{\Phi} \quad (\Phi \text{ constant}) \quad (7)$$

The experimental air specific impulse must be computed from experimental measurements as discussed in the appendix; the theoretical air specific impulse is read from the curves of air specific impulse against equivalence ratio at the burner-inlet temperature applying to the experimental data. It may then be corrected to the combustion pressure used in the actual engine by the method described previously.

A combustion efficiency which is often useful can be defined as the ratio of the theoretical equivalence ratio to the experimental equivalence ratio required to produce a given air specific impulse:

$$\eta_c = \left(\frac{\Phi_t}{\Phi_{\text{exp}}} \right)_{S_a} \quad (S_a \text{ constant}) \quad (8)$$

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Fuel-air ratios may replace equivalence ratios. This definition is valid only for equivalence ratios of 1.0 or less. When the experimental data are obtained at pressures other than 2 atmospheres, a pressure correction may be conveniently applied to the theoretical equivalence ratio as follows: The experimental air specific impulse and combustion pressure are entered on the semilogarithmic graph of theoretical air specific impulse against combustion pressure (parts (e) of the figs.), and a line of constant composition is followed to a combustion pressure of 2 atmospheres. The air specific impulse, adjusted to the 2-atmosphere standard, and the experimental inlet-air temperature are then used on the plots of air specific impulse against inlet-air temperature and equivalence ratio to find the theoretical equivalence ratio. For example, boron burned at an inlet-air temperature of 500° F, a combustion pressure of 0.2 atmosphere, and an equivalence ratio of 1.0 produces an experimental air specific impulse of 180 seconds, which locates point E on figure 4(e). Following the dashed line of constant composition to point F determines a pressure-adjusted air specific impulse of 184.9 seconds. Locating a point in figure 4(b) at 184.9 seconds and at an inlet-air temperature of 500° F determines a theoretical equivalence ratio of 0.885. A combustion efficiency of 0.885 is then found by means of equation (8).

Determination of relative fuel-flow requirements for given engine. - In instances where several fuels are being considered for an engine, it may be desired to know the relative amounts of each fuel required to obtain a fixed thrust level. The curves of air specific impulse against reciprocal fuel-weight specific impulse may conveniently be used for determining the amounts of fuel if advantage is taken of the following assumptions: The combustion efficiency is the same for each fuel, and momentum and other internal pressure losses are nearly the same for each fuel at a given thrust level.

For example, a ram-jet engine is operated with octene-1 or any other reasonably similar hydrocarbon at a fuel-air ratio of 0.05, an inlet-air temperature of 100° F, and a combustion pressure of 2 atmospheres. From figure 1(c), the air specific impulse for octene-1 at this fuel-air ratio and inlet-air temperature is 153.4 seconds; the reciprocal fuel-weight specific impulse is 0.000326 seconds⁻¹. By use of the curves (fig. parts (c)) of reciprocal fuel-weight specific impulse against air specific impulse for the other fuels at an inlet-air temperature of 100° F, fuel-air ratios, reciprocal fuel-weight specific impulses, and relative fuel flows required to produce an air specific impulse of 153.4 seconds are determined. They are presented in the following table:

Fuel	Fuel-air ratio	Reciprocal fuel-weight specific impulse, sec ⁻¹	Relative fuel flow
Octene-1	0.05	0.326X10 ⁻³	1.00
50-Percent-magnesium slurry	.065	.423	1.30
Boron	.054	.353	1.08
Pentaborane	.042	.274	.84
Diborane	.038	.247	.76

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The relative fuel flow can be defined in this case as either the ratio of the reciprocal fuel-weight specific impulse of the substitute fuel to that of octene-1, or the ratio of the fuel-air ratio of the substitute fuel to that of octene-1, since, at a constant air specific impulse, the fuel-weight specific impulses of two fuels are in the ratio

$$\frac{s_{f,w_1}}{s_{f,w_2}} = \frac{\left(\frac{w_f}{w_a}\right)_2}{\left(\frac{w_f}{w_a}\right)_1} \quad (9)$$

(see eq. (2)).

A correction of fuel-air ratios for combustion pressures other than 2 atmospheres can be made in the manner previously described for equivalence ratios used to determine combustion efficiency.

CONCLUDING REMARKS

The effect of inlet-air temperature, combustion pressure, and equivalence ratio upon theoretical air specific impulse performance was investigated for the following fuels: octene-1, 50-percent-magnesium slurry, boron, pentaborane, diborane, hydrogen, carbon, and aluminum. Considered were inlet-air temperatures from 100° to 900° F at a combustion pressure of 2 atmospheres and a combustion pressure of 0.2 atmosphere at an inlet-air temperature of 100° F.

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The benefit to air specific impulse of an increase in inlet-air temperature was observed to decrease at higher equivalence ratios, because of increasing specific heats and dissociation of the combustion products resulting from higher combustion temperatures. The fuel consumption of pentaborane and diborane remained below that of octene-1 despite the adverse affect of boron oxide vaporization on the performance of boron-containing fuels at combustion temperatures exceeding 3000° R; the fuel consumption of boron became higher than that of octene-1 above this temperature. The air specific impulse performance of boron, diborane, and pentaborane exceeded that of octene-1 at high equivalence ratios. An increase in combustion pressure from 0.2 to 2.0 atmospheres caused gains in air specific impulse at higher equivalence ratios of as much as 5 seconds.

Because a limited range of inlet-air temperatures and combustion pressures were considered, methods of extending the data to other inlet conditions were presented. Determination of air specific impulse efficiency and combustion efficiency for experimental combustion by means of the theoretical data herein was discussed. The use of the theoretical performance data in determining the relative flows of the various fuels to an engine operating at a fixed thrust level was also discussed.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, July 14, 1953

APPENDIX - COMPUTATION OF AIR SPECIFIC IMPULSE FROM
EXPERIMENTAL DATA

The determination of air specific impulse efficiency requires that the experimental air specific impulse be computable. Suitable measurements of pressure, drag, and thrust must be made on the experimental engine or combustor to permit computation of the stream thrust at the end of the exhaust nozzle:

$$F_e = \left(pA + \frac{wV}{g} \right)_e \quad (A1)$$

This equation is then reduced to the stream thrust function at a condition of sonic flow

$$F_e^* = \frac{\left(pA + \frac{wV}{g} \right)_e}{\varphi(M_e)} \quad (A2)$$

where

$$\varphi(M_e) = \frac{1 + \gamma_e M_e^2}{M_e \sqrt{2(\gamma_e + 1) \left(1 + \frac{\gamma_e - 1}{2} M_e^2 \right)}} \quad (A3)$$

The experimental air specific impulse is then

$$S_a = \frac{F_e^*}{w_a} \quad (A4)$$

The Mach number at the exhaust-nozzle outlet can be estimated from the equation

$$M_e = \sqrt{\frac{w g_e e V_e}{\gamma_e g p_e A_e}} \quad (A5)$$

For convenience, $\varphi(M_e)$ may be found from tables 30 to 35 of reference 14 as the term F/F^* . The expression $\varphi(M)$ is relatively insensitive to γ , in the neighborhood of M equal to 1, as shown in the following table:

M	$F/F^* = \Phi(M_e)$	
	γ_e	
	1.1	1.4
0.7	1.0599	1.0451
.8	1.0231	1.0185
.9	1.0051	1.0034
1.0	1.0000	1.0000
1.1	1.0041	1.0030
1.2	1.0148	1.0108
1.3	1.0305	1.0217

It must be observed that if M_e is determined by equation (A5), then the error in $\Phi(M_e)$, resulting from an incorrect choice of γ_e , will exceed that shown in the preceding table. Data in reference 3 show that a satisfactory value of γ_e at high combustion temperatures (or high air specific impulse) would be 1.2 to 1.3; at low air specific impulse or combustion temperature, values of 1.3 to 1.4 can be employed.

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TABLE I. - THERMAL PROPERTIES OF SOME FUELS

Fuel	Formula	Phase	Temperature, °K	Heat of formation, kcal/mole	Heat of combustion ^a			Enthalpy assigned, (H_T^0) _f , kcal/mole
					kcal/mole	Btu/lb	Phase of combustion products	
Octene-1	C ₈ H ₁₆	Liquid	298.16		^{b, c} 1185.12	18,999	(H ₂ O) _g , (CO ₂) _g	1263.28
50-Percent- magnesium slurry	4.61382 Mg + C ₈ H ₁₆	Crystal Liquid	298.16	^d Note		14,820	(MgO) _{cr} , (CO ₂) _g (H ₂ O) _g	341.56
Boron	B	Crystal	298.16	^e 0.0	^e 151.0	25,104	(B ₂ O ₃) _{cr}	173.58
Pentaborane	B ₅ H ₉	Liquid	298.16	^e 7.8	^e 1022.9	29,127	(H ₂ O) _g , (B ₂ O ₃) _{cr}	1187.18
Diborane	B ₂ H ₆	Liquid	180.63		^{e, f} 478.1	31,061	(H ₂ O) _g , (B ₂ O ₃) _{cr}	557.8
Hydrogen	H ₂	Liquid	20.39		^{e, g} 5.903	49,881	(H ₂ O) _g	67.54
Carbon	C	Crystal (graphite)	298.16	^e 0.0	^e 94.052	14,087	(CO ₂) _g	92.18
Aluminum	Al	Crystal	298.16	^e 0.0	^e 199.545	13,309	^h (Al ₂ O ₃) _{cr}	234.70

^aFuel at temperature shown; oxygen and combustion products at 298.16° K.^bHeat of vaporization, 9.85 kcal/mole from reference 15.^cReference 16.^dHeat of formation of Mg from reference 17.^eReference 17.^fEnthalpy change between 180.63° and 298.16° K from reference 18.^gHeat of vaporization and enthalpy change between 20.39° and 298.16° K from reference 19.^h—Crystal.

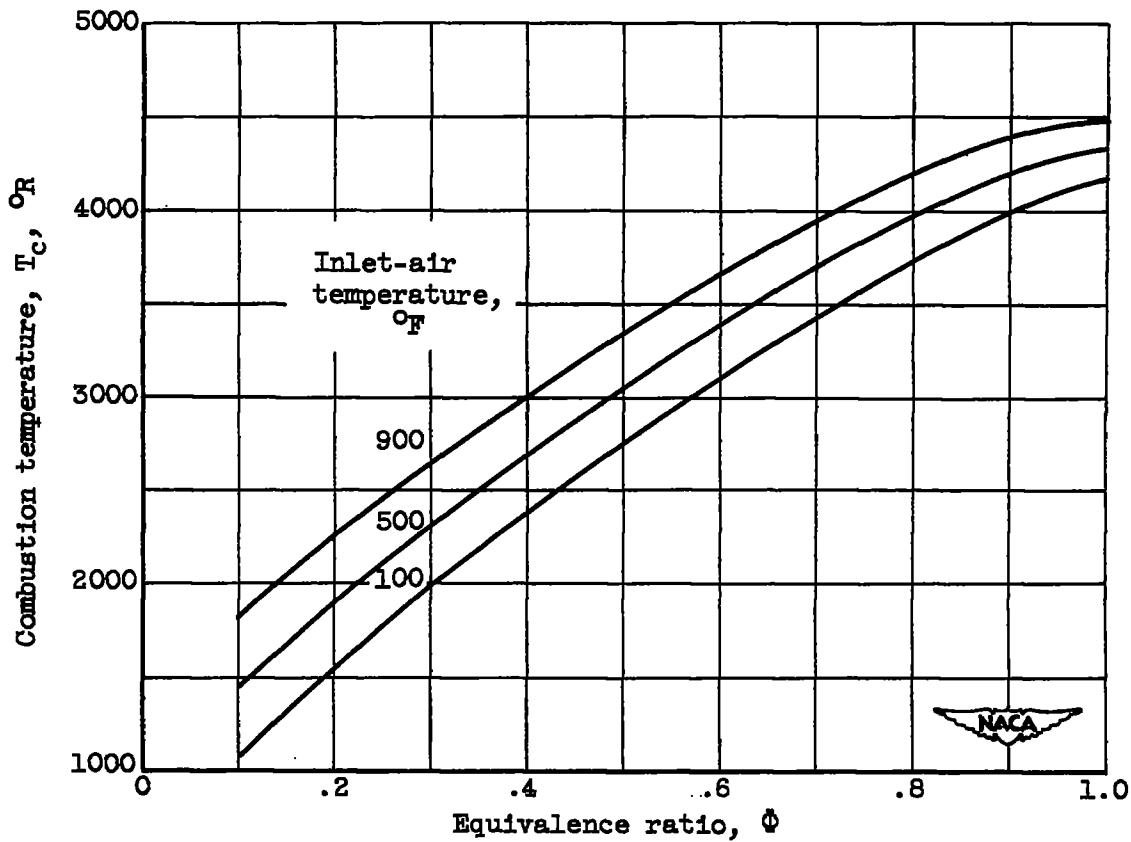
TABLE III. - PRODUCTS CONSIDERED POSSIBLE AS A RESULT OF ADIABATIC COMBUSTION

Product ^a	Fuel							
	Octene-1	Boron	Penta-borane	Diborane	Hydrogen	Carbon	50-Percent-magnesium slurry	Aluminum
O ₂	x	x	x	x	x	x	x	x
N ₂	x	x	x	x	x	x	x	x
CO ₂	x					x	x	
H ₂ O	x		x	x	x		x	
H ₂	x		x	x	x		x	
CO	x					x	x	
C	x					x	x	
H	x		x	x	x		x	
O	x	x	x	x	x	x	x	x
N	x	x	x	x	x	x	x	x
OH	x	x	x	x	x	x	x	
NO	x	x	x	x	x	x	x	x
(MgO) _s								
(Al ₂ O ₃) _{s,l,g}								x
Al								x
AlO								x
(B ₂ O ₃) _{s,l,g}		x	x	x				
B	x	x	x	x				
BO	x	x	x	x				
BH			x	x				

^aGaseous except as noted.

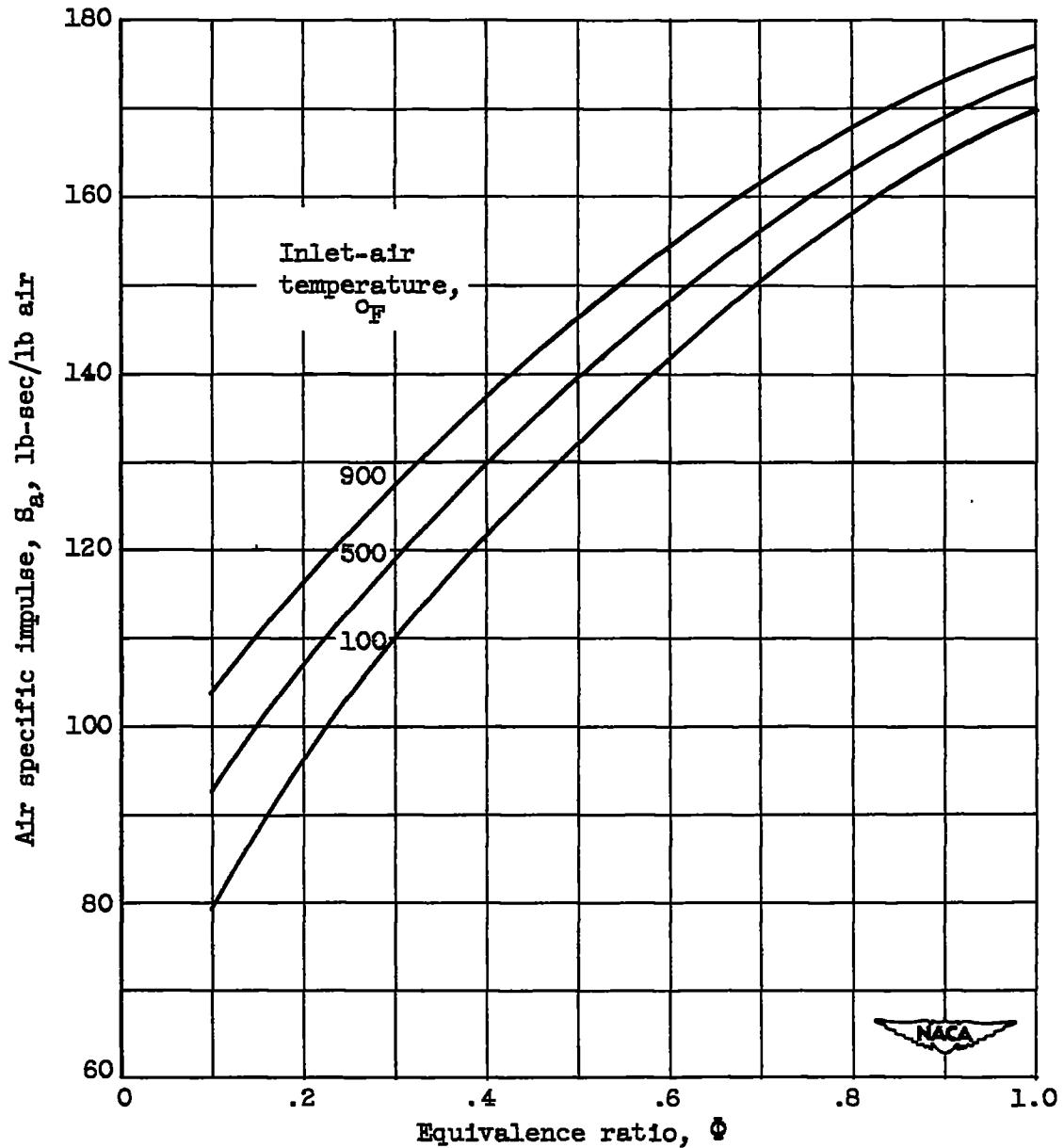


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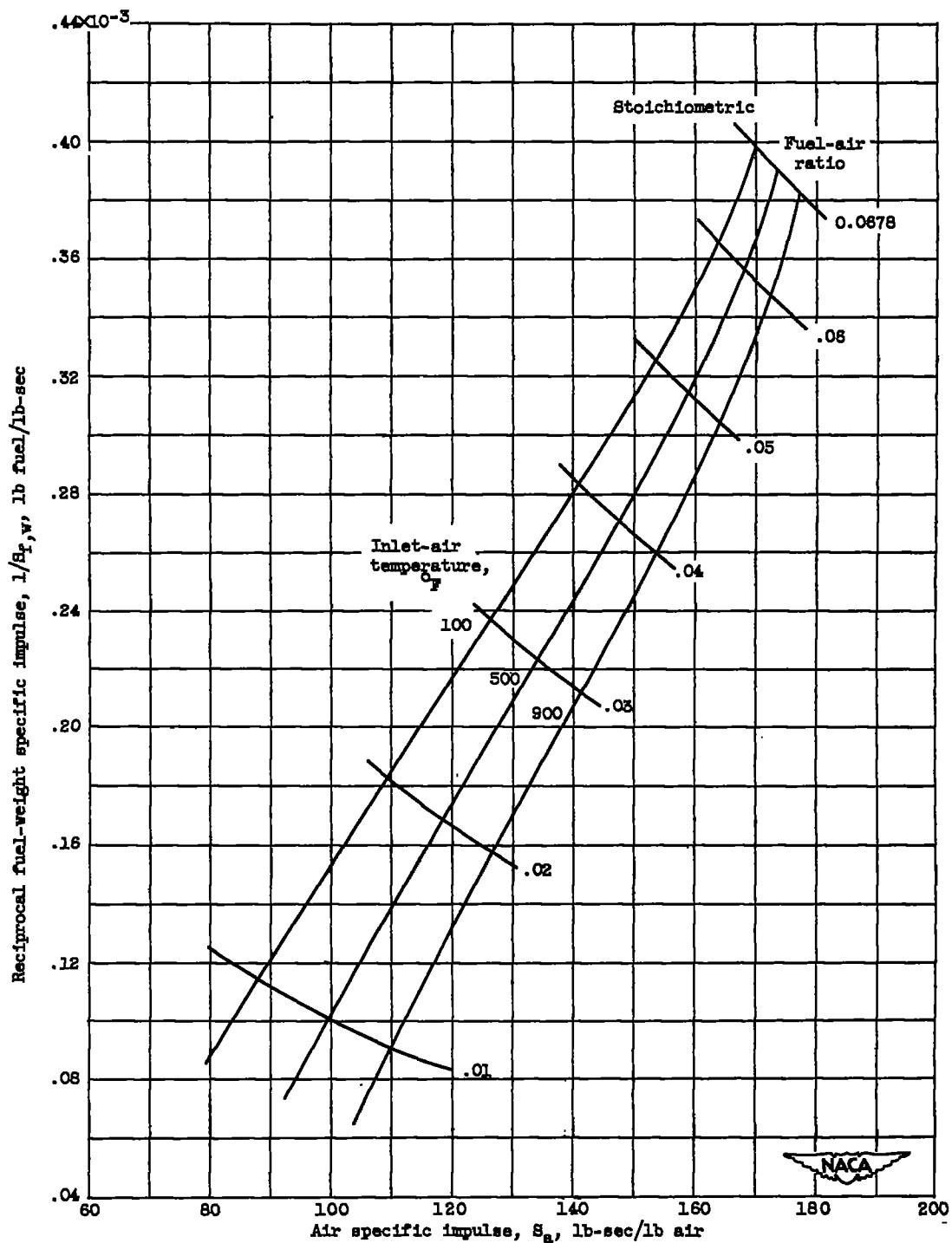
(a) Variation of combustion temperature with equivalence ratio and inlet-air temperature. Combustion pressure, 2 atmospheres.

Figure 1. - Effect of ram-jet combustor inlet conditions on theoretical combustion performance of liquid octene-1.



(b) Variation of air specific impulse with inlet-air temperature and equivalence ratio. Combustion pressure, 2 atmospheres.

Figure 1. - Continued. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of liquid octene-1.

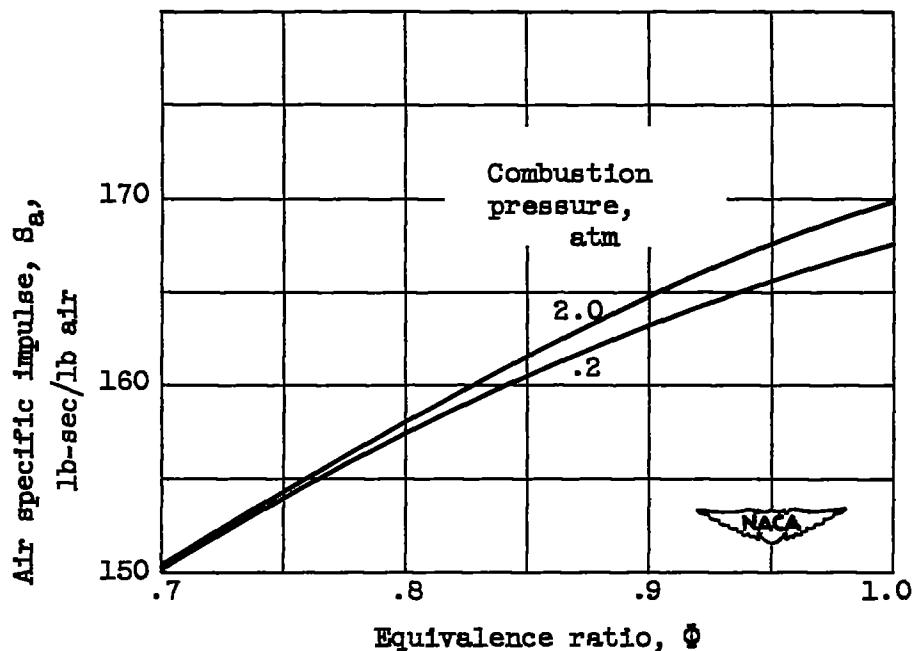


(c) Variation of reciprocal fuel-weight specific impulse with air specific impulse and inlet-air temperature. Combustion pressure, 2 atmospheres.

Figure 1. - Continued. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of liquid octene-1.

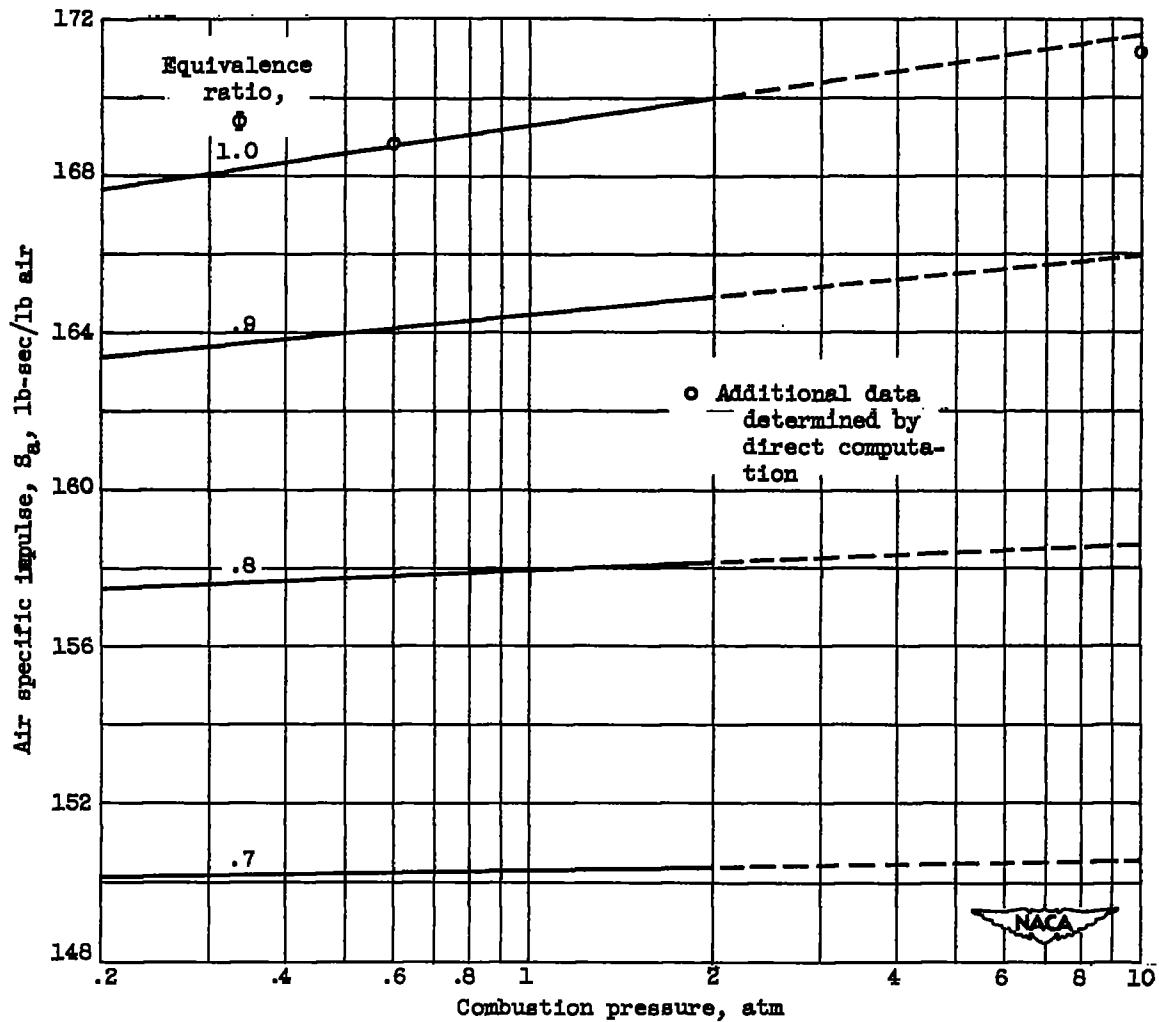
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(d) Variation of air specific impulse with combustion pressure and equivalence ratio. Inlet-air temperature, 100° F.

Figure 1. - Continued. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of liquid octene-1.

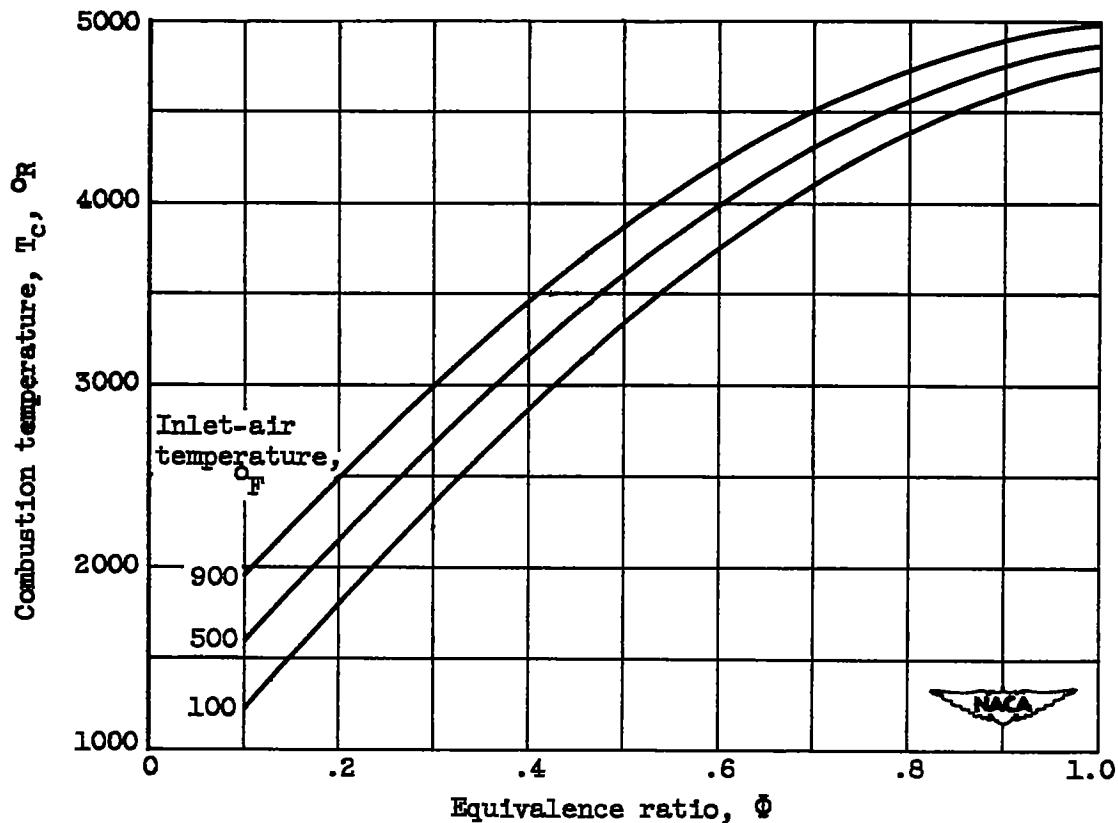


(e) Variation of air specific impulse with combustion pressure at selected equivalence ratios. Inlet-air temperature, 100° F.

Figure 1. - Concluded. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of liquid octene-1.

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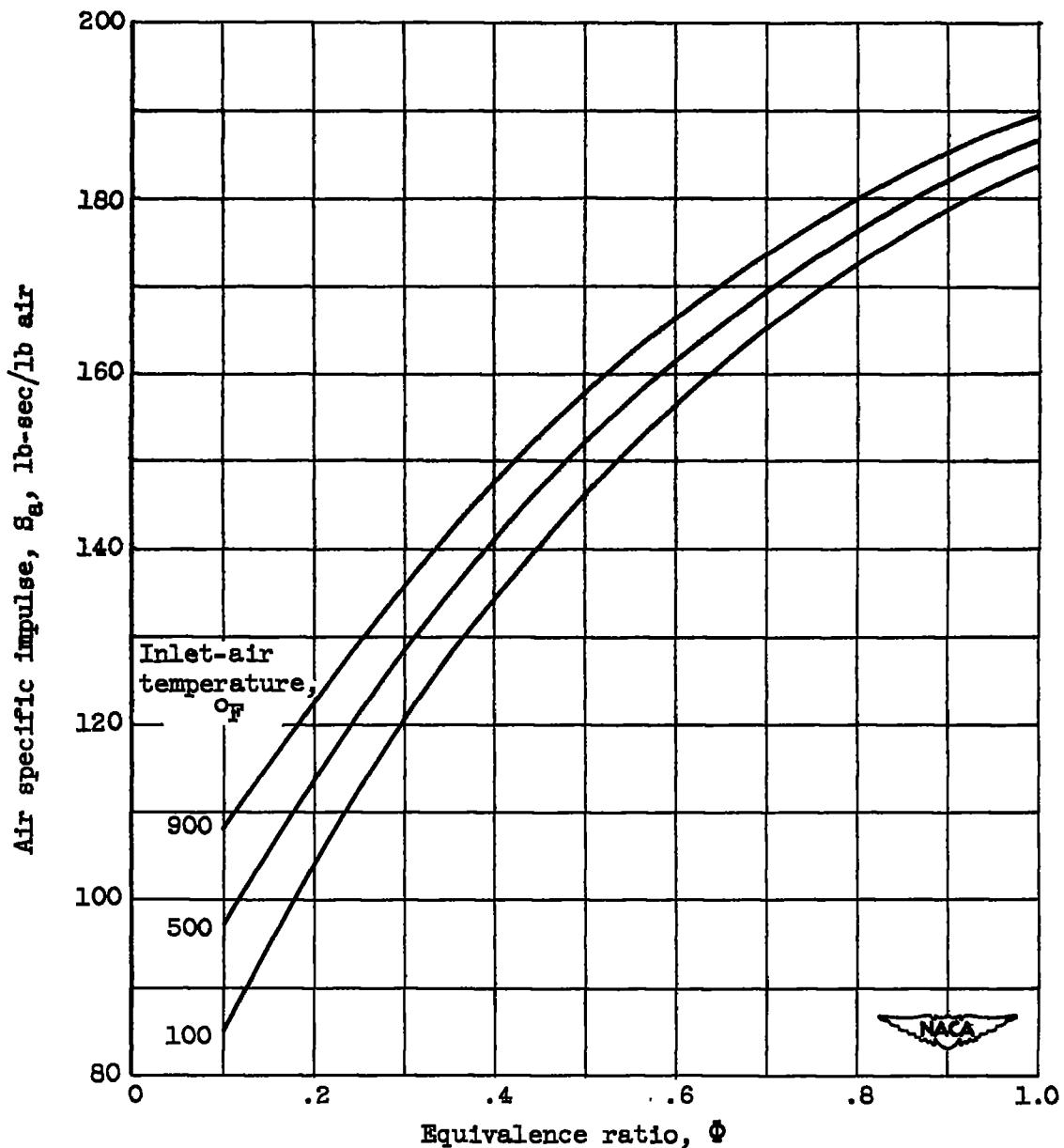
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(a) Variation of combustion temperature with equivalence ratio and inlet-air temperature. Combustion pressure, 2 atmospheres.

Figure 2. - Effect of ram-jet combustor inlet conditions on theoretical combustion performance of 50-percent-magnesium slurry.

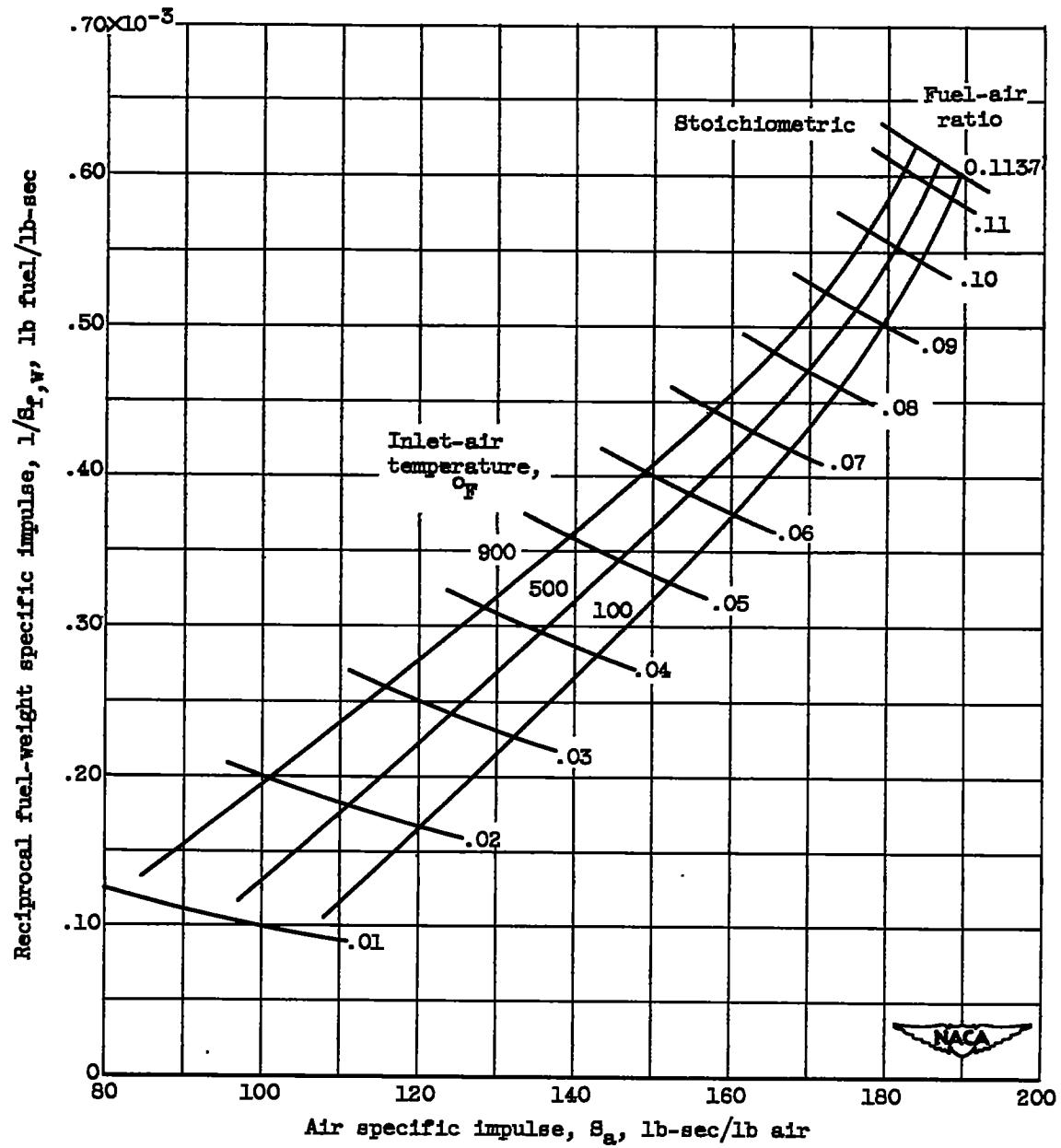
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(b) Variation of air specific impulse with inlet-air temperature and equivalence ratio. Combustion pressure, 2 atmospheres.

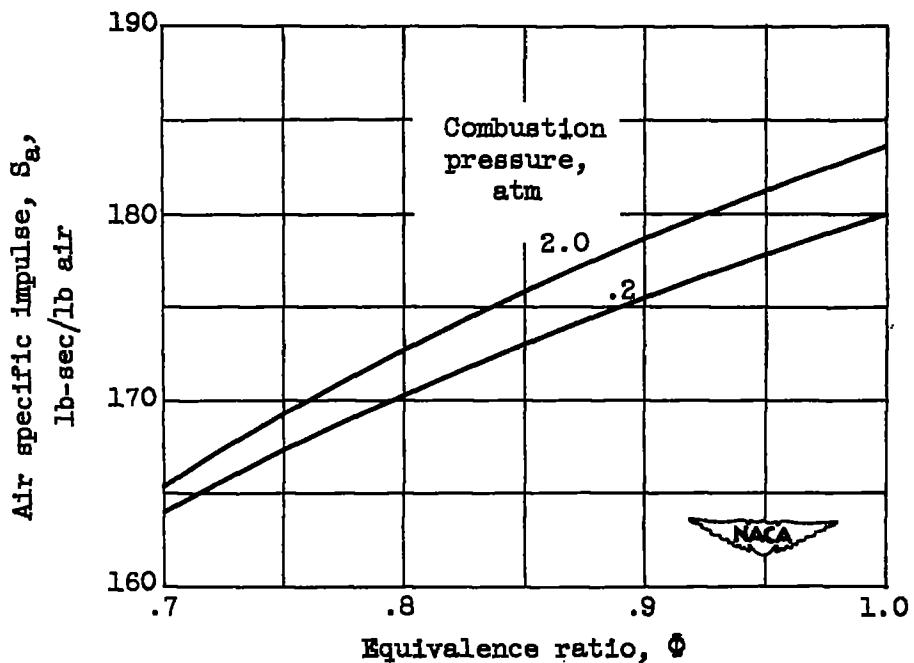
Figure 2. - Continued. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of 50-percent-magnesium slurry.

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(c) Variation of reciprocal fuel-weight specific impulse with air specific impulse and inlet-air temperature. Combustion pressure, 2 atmospheres.

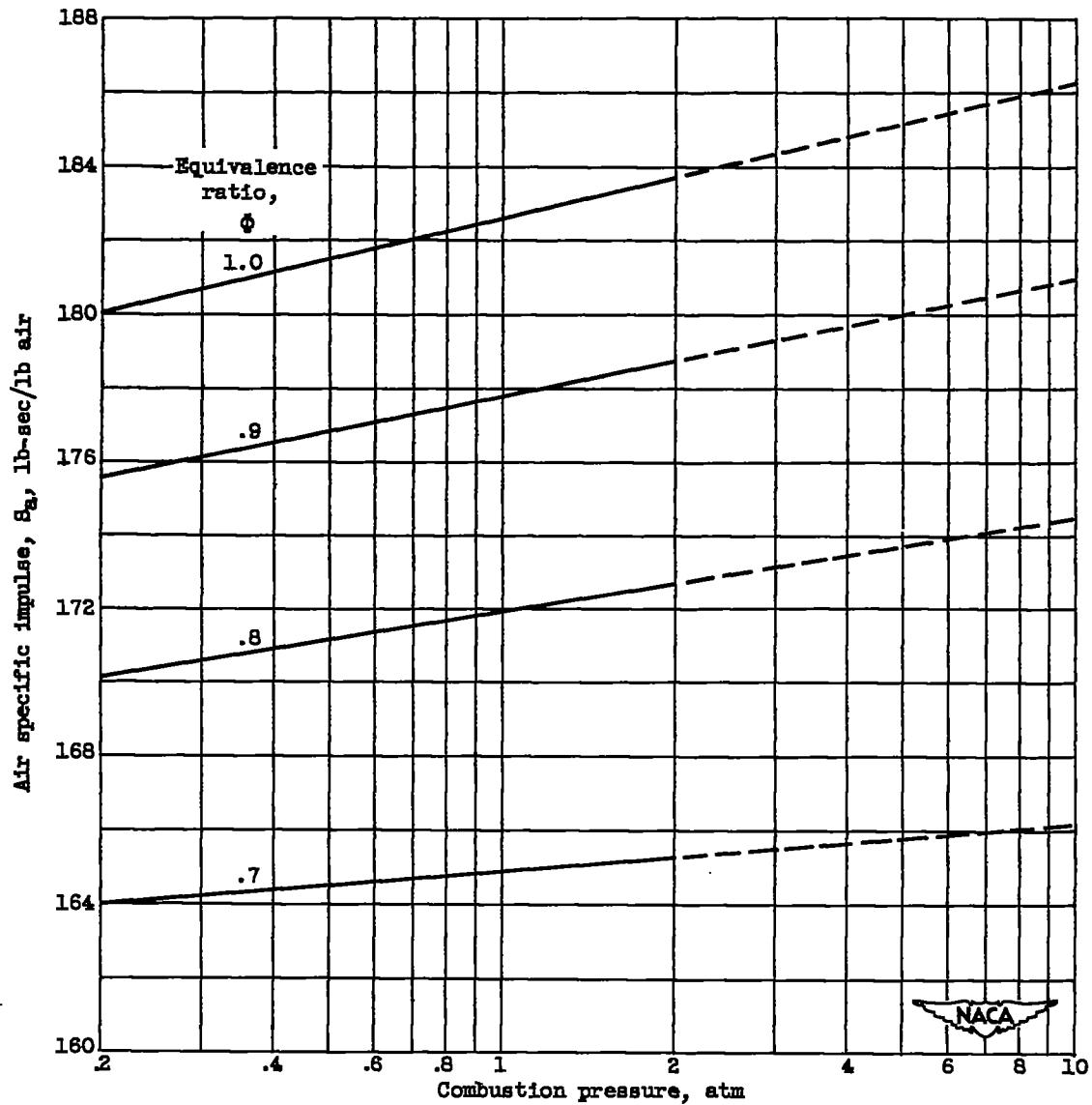
Figure 2. - Continued. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of 50-percent-magnesium slurry.



(d) Variation of air specific impulse with combustion pressure and equivalence ratio.
Inlet-air temperature, 100° F.

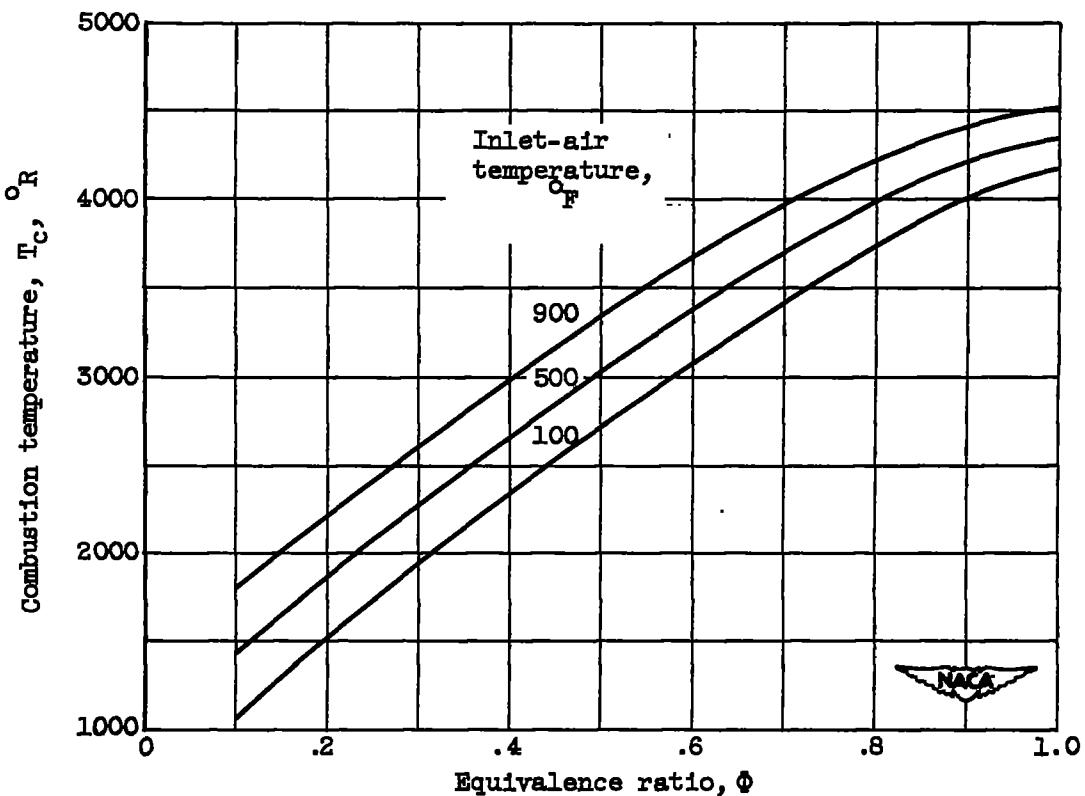
Figure 2. - Continued. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of 50-percent-magnesium slurry.

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(e) Variation of air specific impulse with combustion pressure at selected equivalence ratios. Inlet-air temperature, 100° F.

Figure 2. - Concluded. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of 50-percent-magnesium slurry.

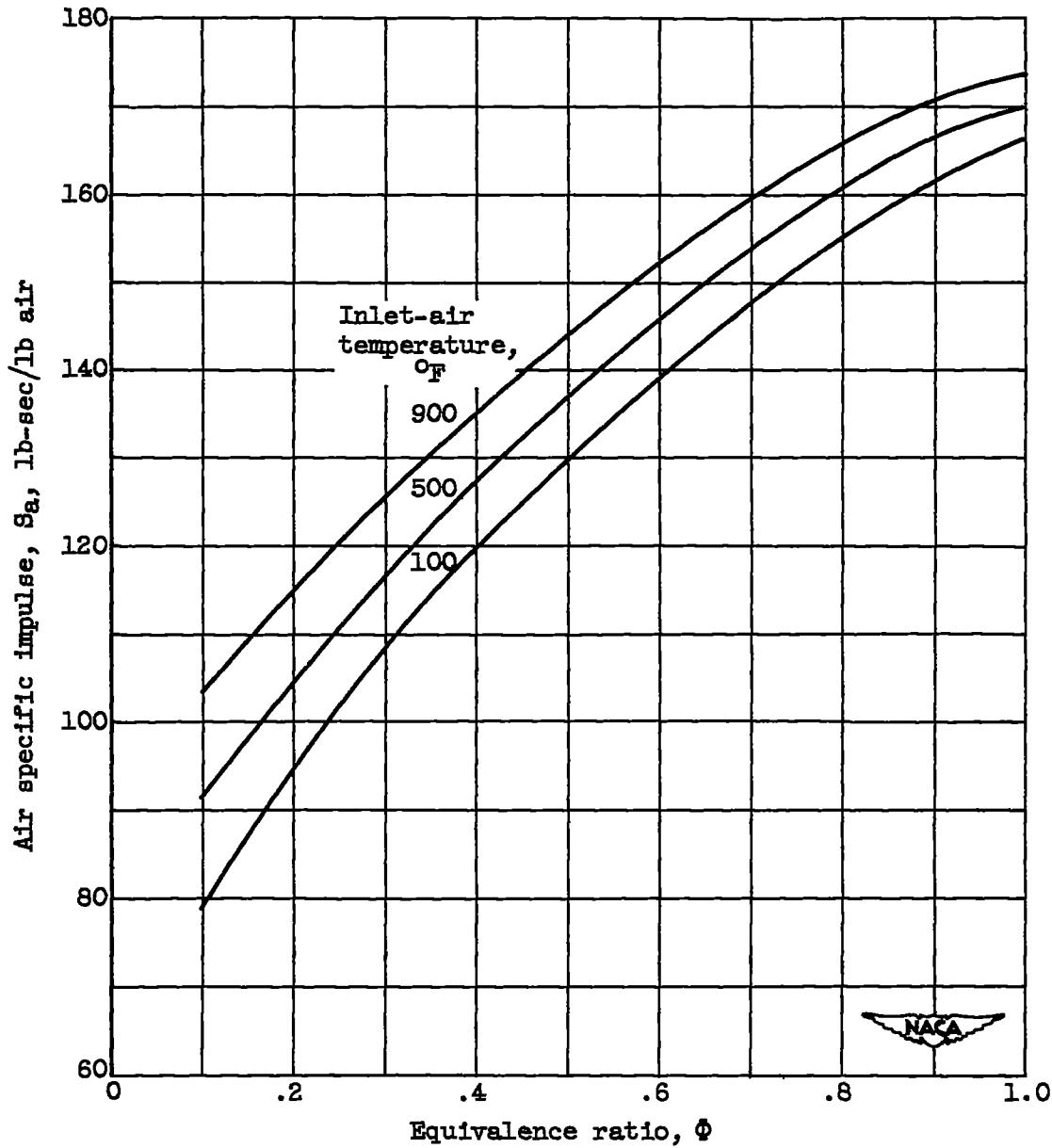


(a) Variation of combustion temperature with equivalence ratio and inlet-air temperature. Combustion pressure, 2 atmospheres.

Figure 3. - Effect of ram-jet combustor inlet conditions on theoretical combustion performance of carbon (graphite).

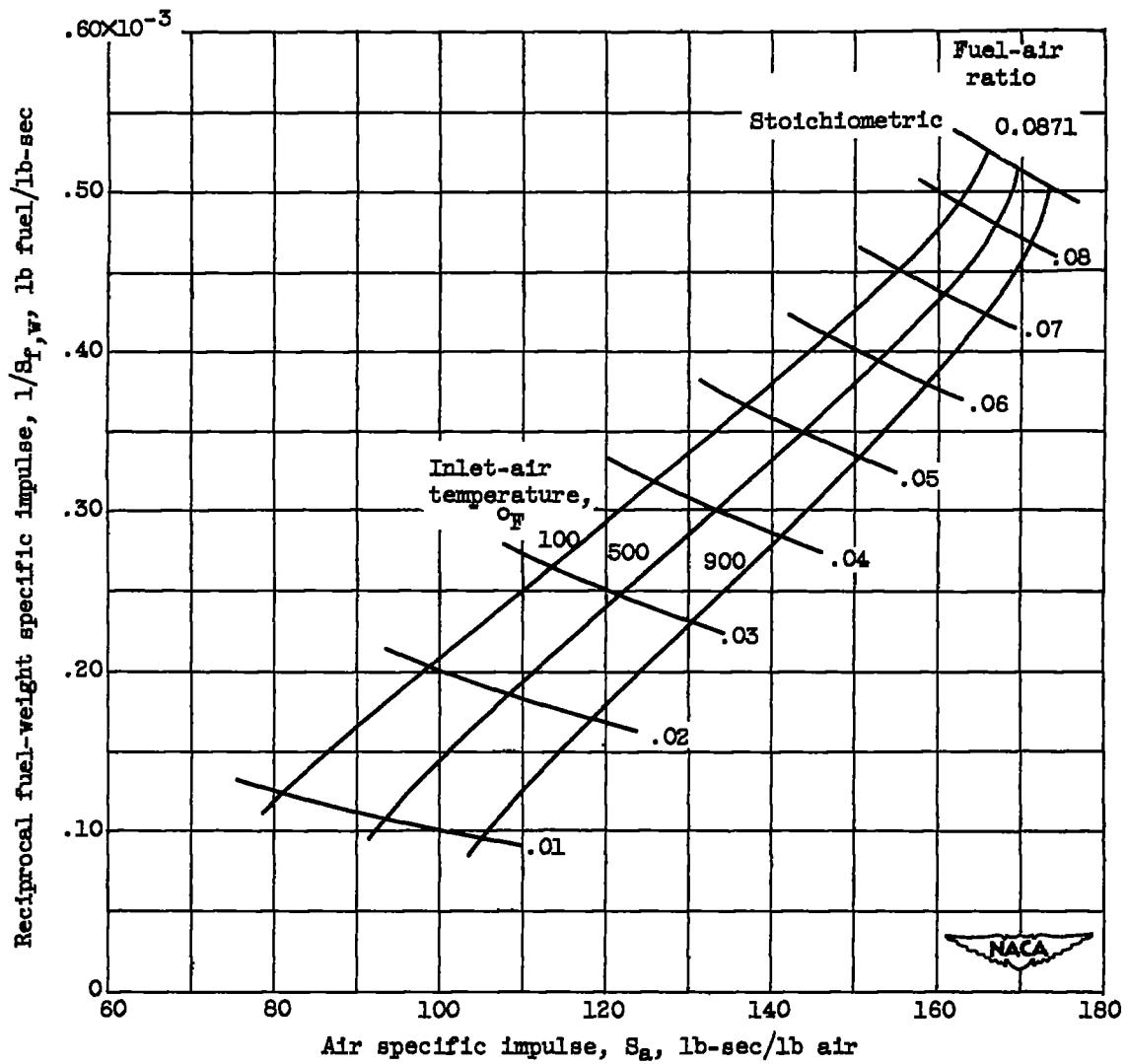
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(b) Variation of air specific impulse with equivalence ratio and inlet-air temperature. Combustion pressure, 2 atmospheres.

Figure 3. - Continued. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of carbon (graphite).

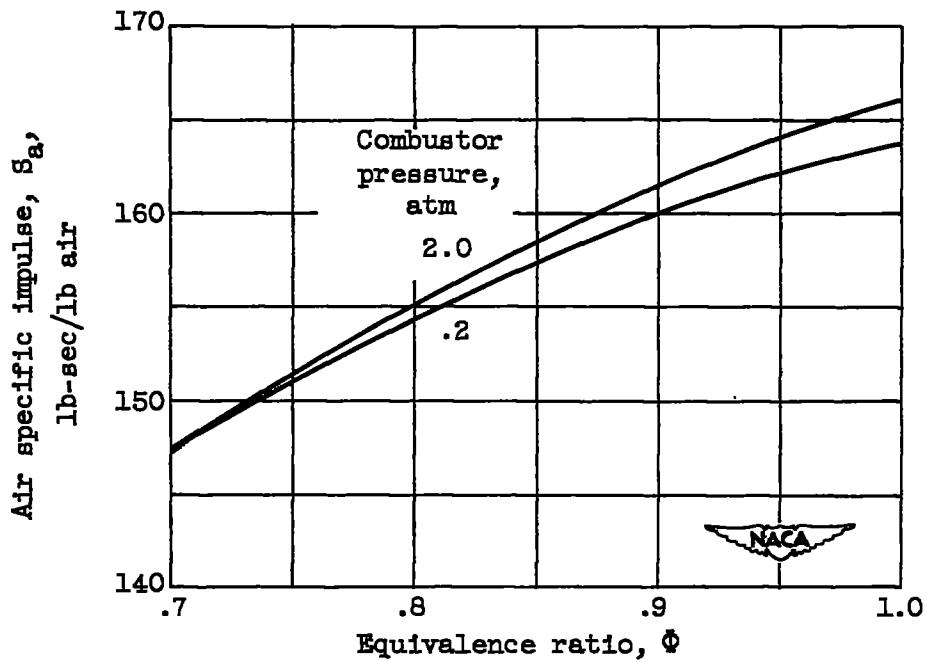


(c) Variation of reciprocal fuel-weight specific impulse with air specific impulse and inlet-air temperature. Combustion pressure, 2 atmospheres.

Figure 3. - Continued. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of carbon (graphite).

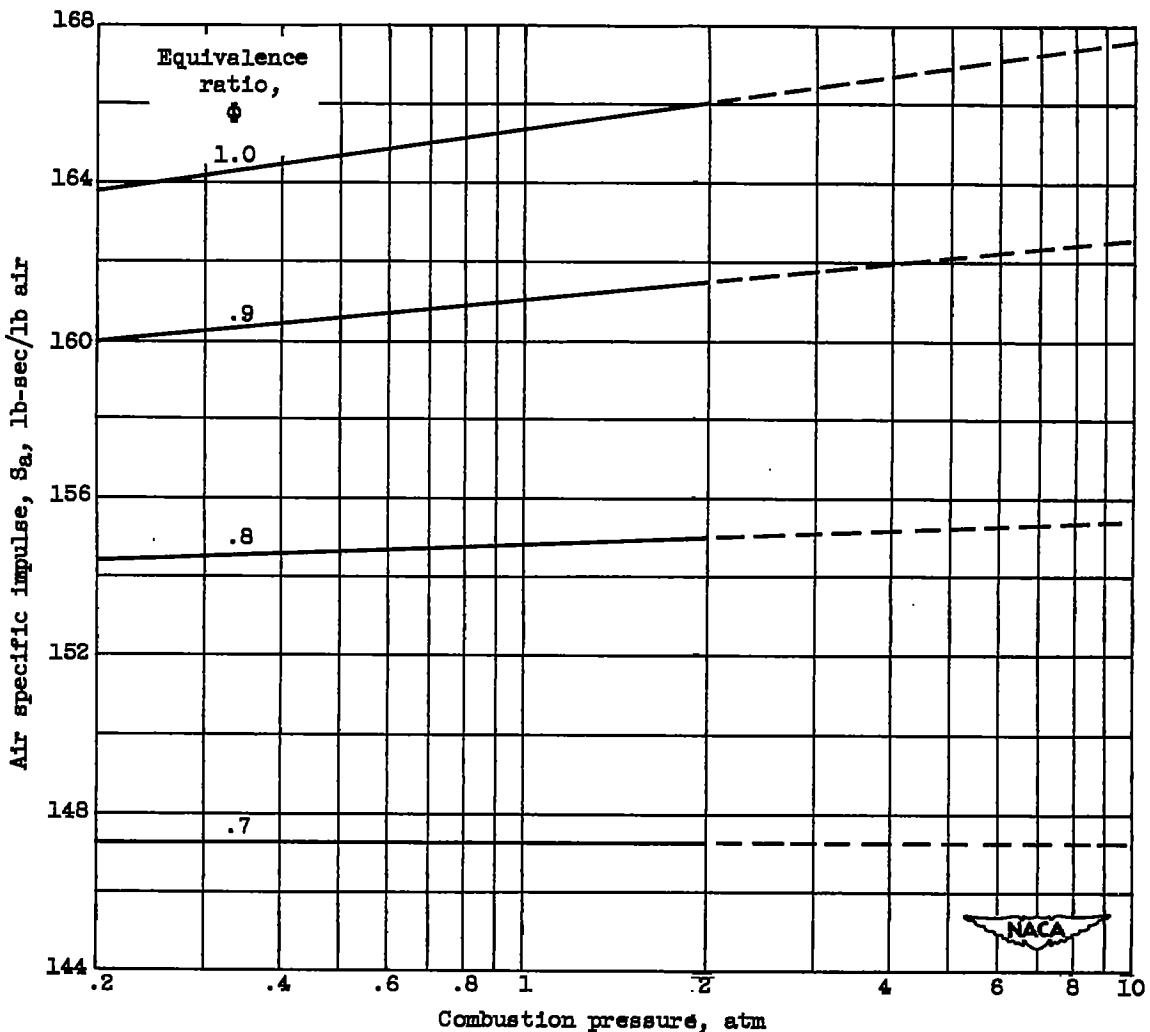
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(d) Variation of air specific impulse with combustion pressure and equivalence ratio.
Inlet-air temperature, 100° F.

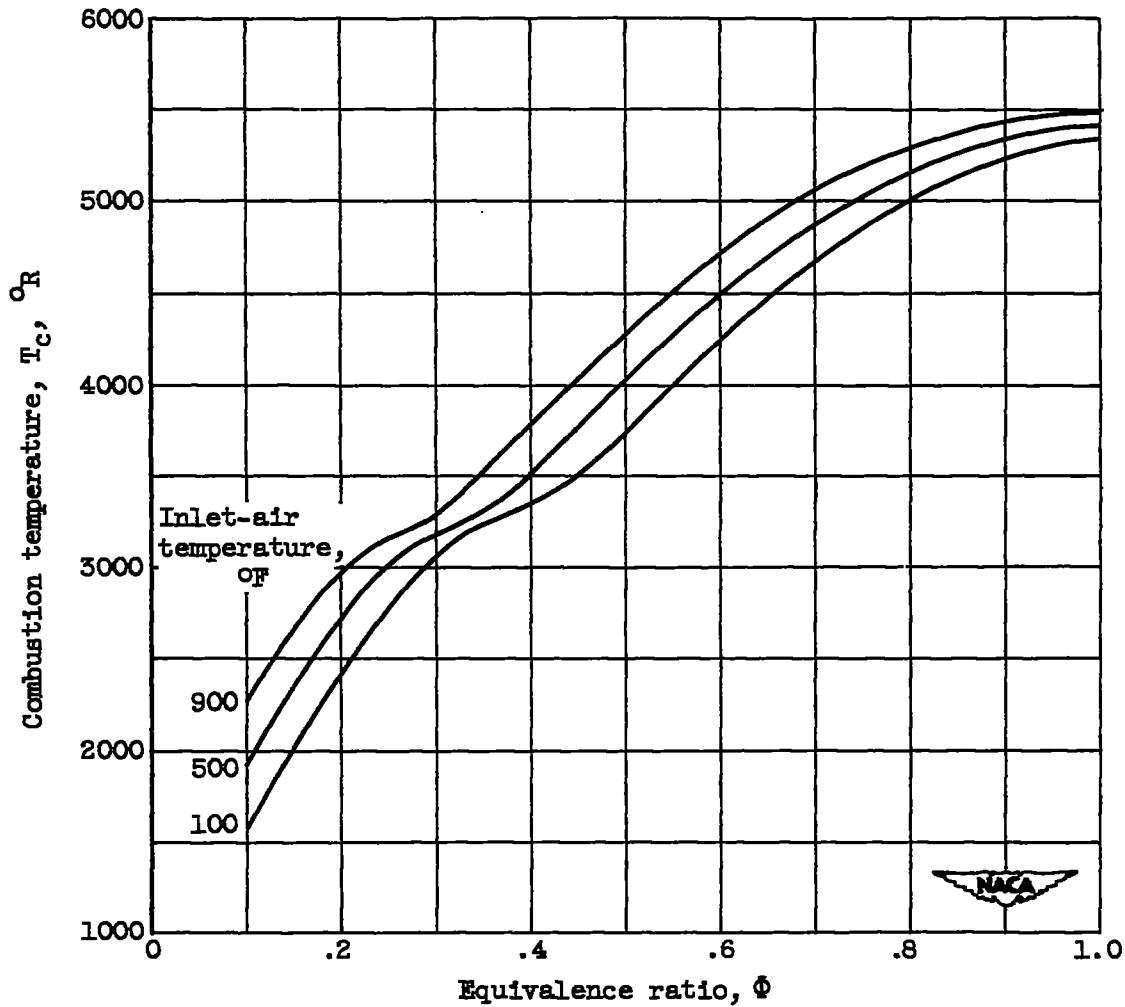
Figure 3. - Continued. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of carbon (graphite).



(e) Variation of air specific impulse with combustion pressure at selected equivalence ratios. Inlet-air temperature, 100° F.

Figure 3. - Concluded. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of carbon (graphite).

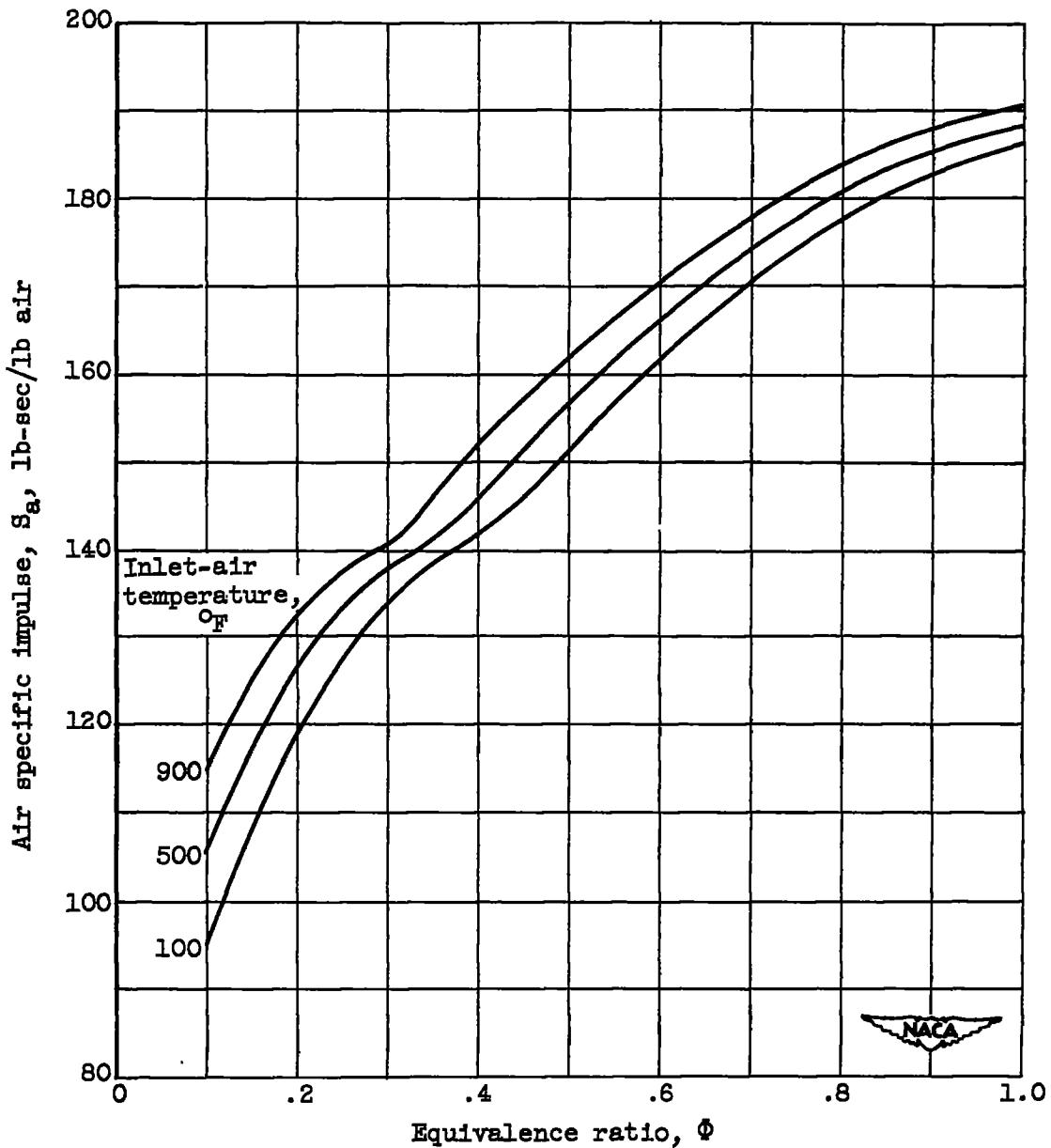
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(a) Variation of combustion temperature with equivalence ratio and inlet-air temperature. Combustion pressure, 2 atmospheres.

Figure 4. - Effect of ram-jet combustor inlet conditions on theoretical combustion performance of crystalline boron.

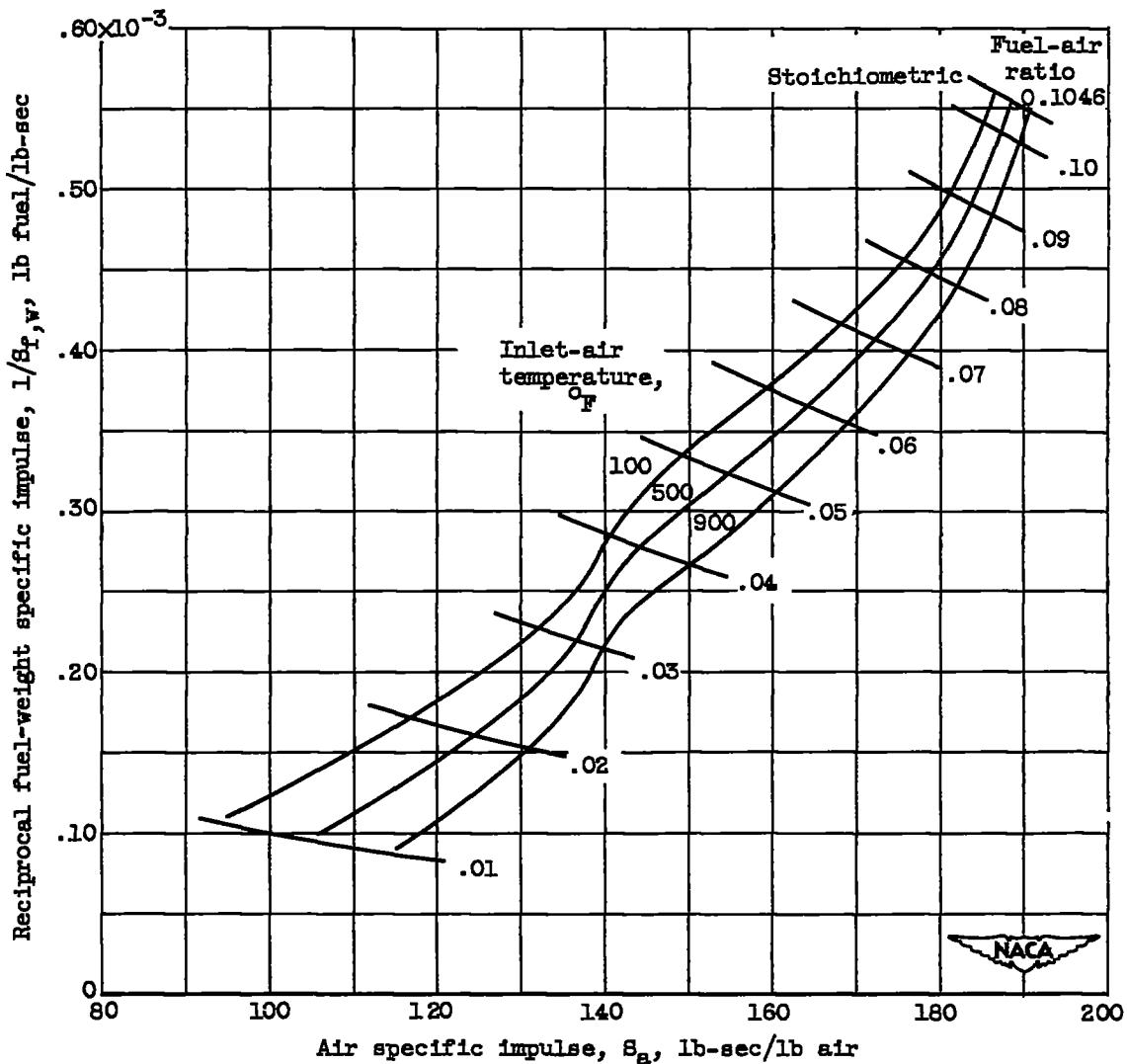
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(b) Variation of air specific impulse with inlet-air temperature and equivalence ratio. Combustion pressure, 2 atmospheres.

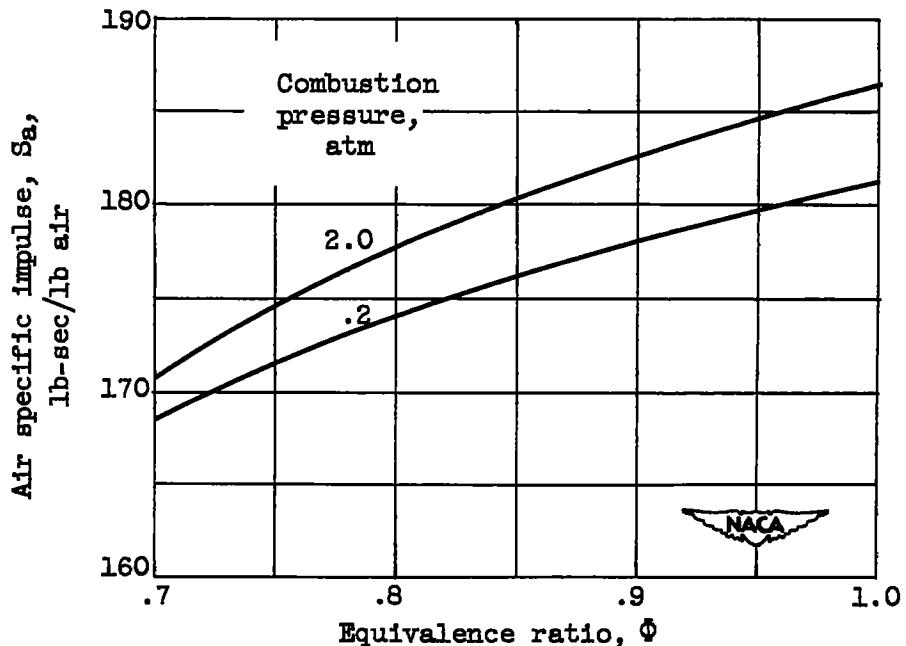
Figure 4. - Continued. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of crystalline boron.

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(c) Variation of reciprocal fuel-weight specific impulse with air specific impulse and inlet-air temperature. Combustion pressure, 2 atmospheres.

Figure 4. - Continued. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of crystalline boron.

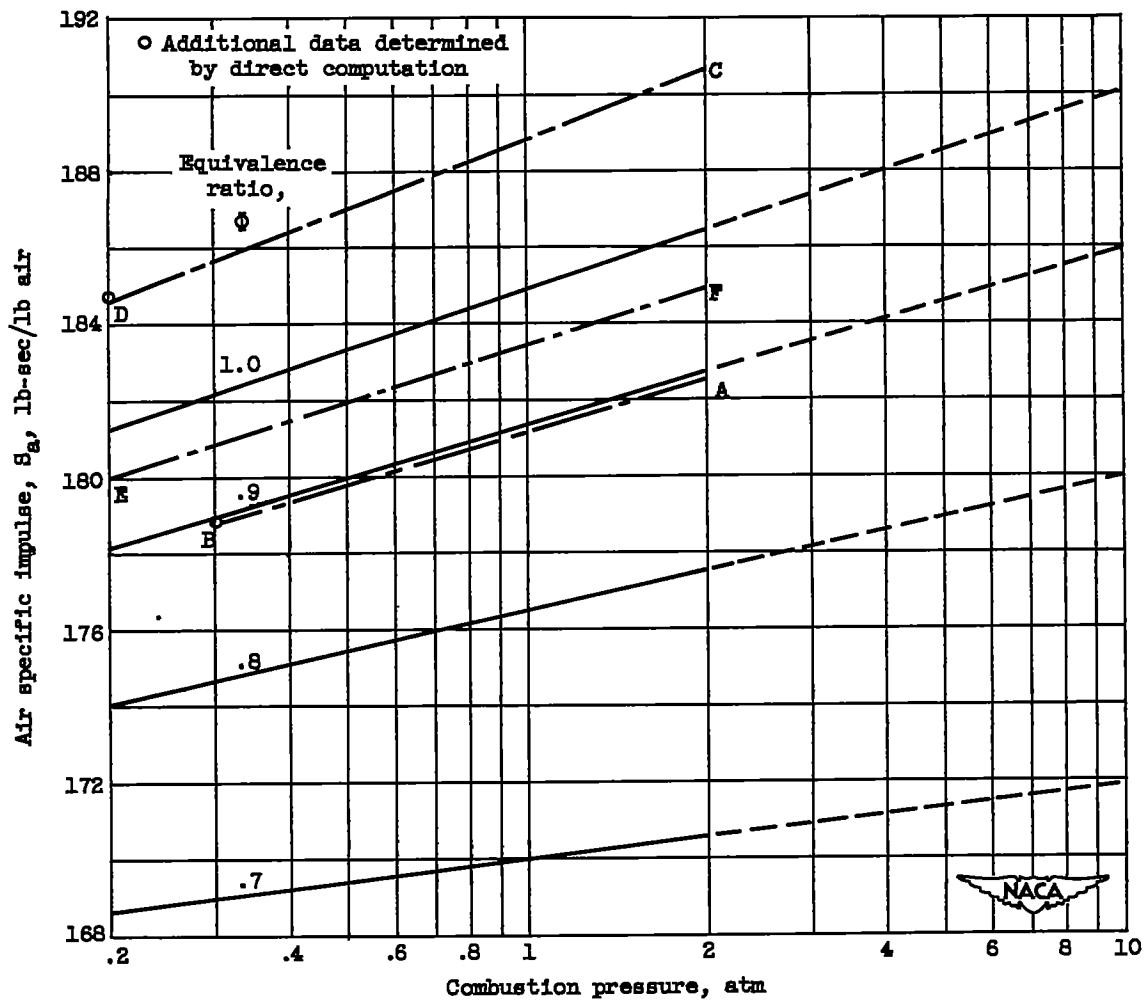


(d) Variation of air specific impulse with combustion pressure and equivalence ratio.
Inlet-air temperature, 100° F.

Figure 4. - Continued. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of crystalline boron.

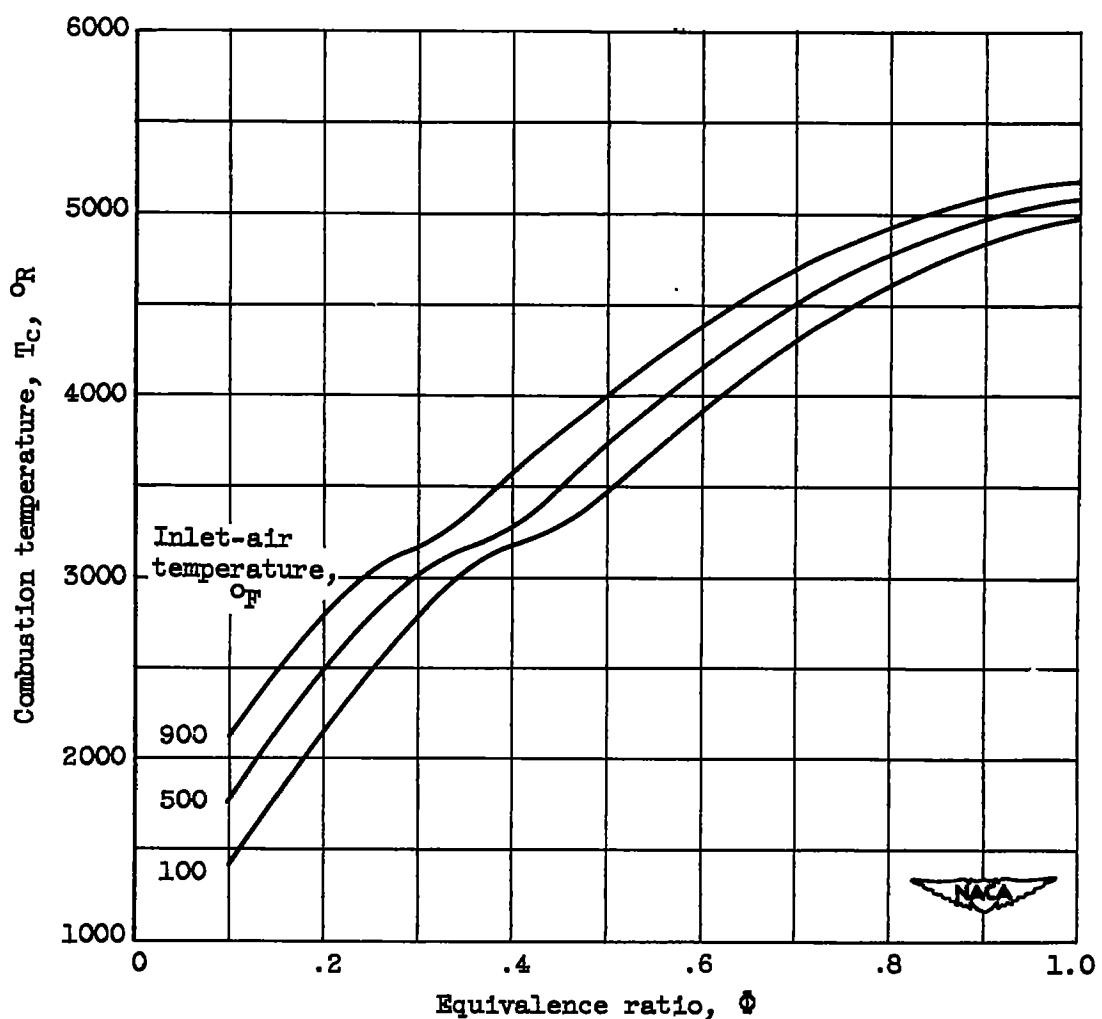
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(e) Variation of air specific impulse with combustion pressure at selected equivalence ratios. Inlet-air temperature, 100° F.

Figure 4. - Concluded. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of crystalline boron.

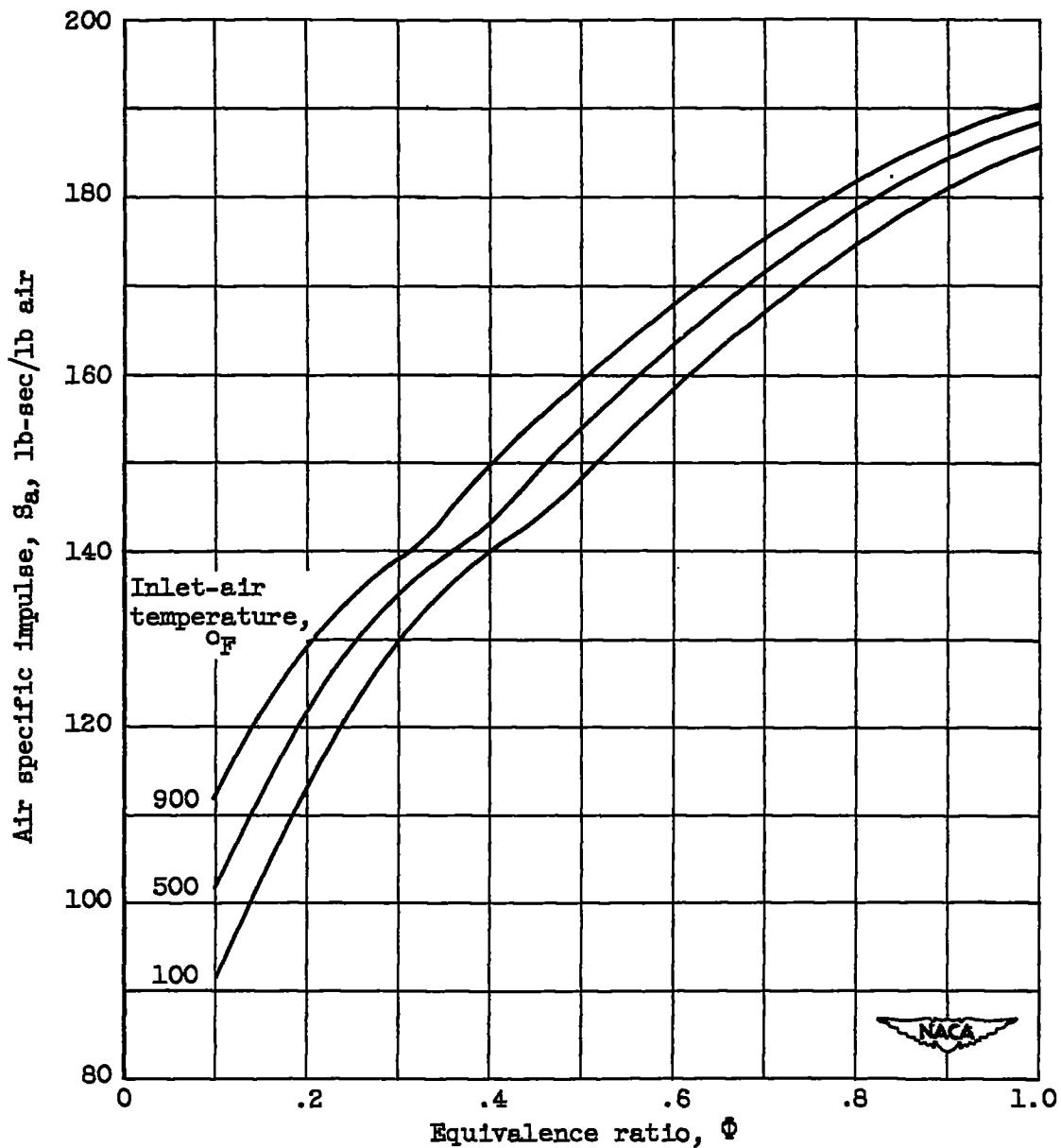


(a) Variation of combustion temperature with equivalence ratio and inlet-air temperature. Combustion pressure, 2 atmospheres.

Figure 5. - Effect of ram-jet combustor inlet conditions on theoretical combustion performance of liquid pentaborane.

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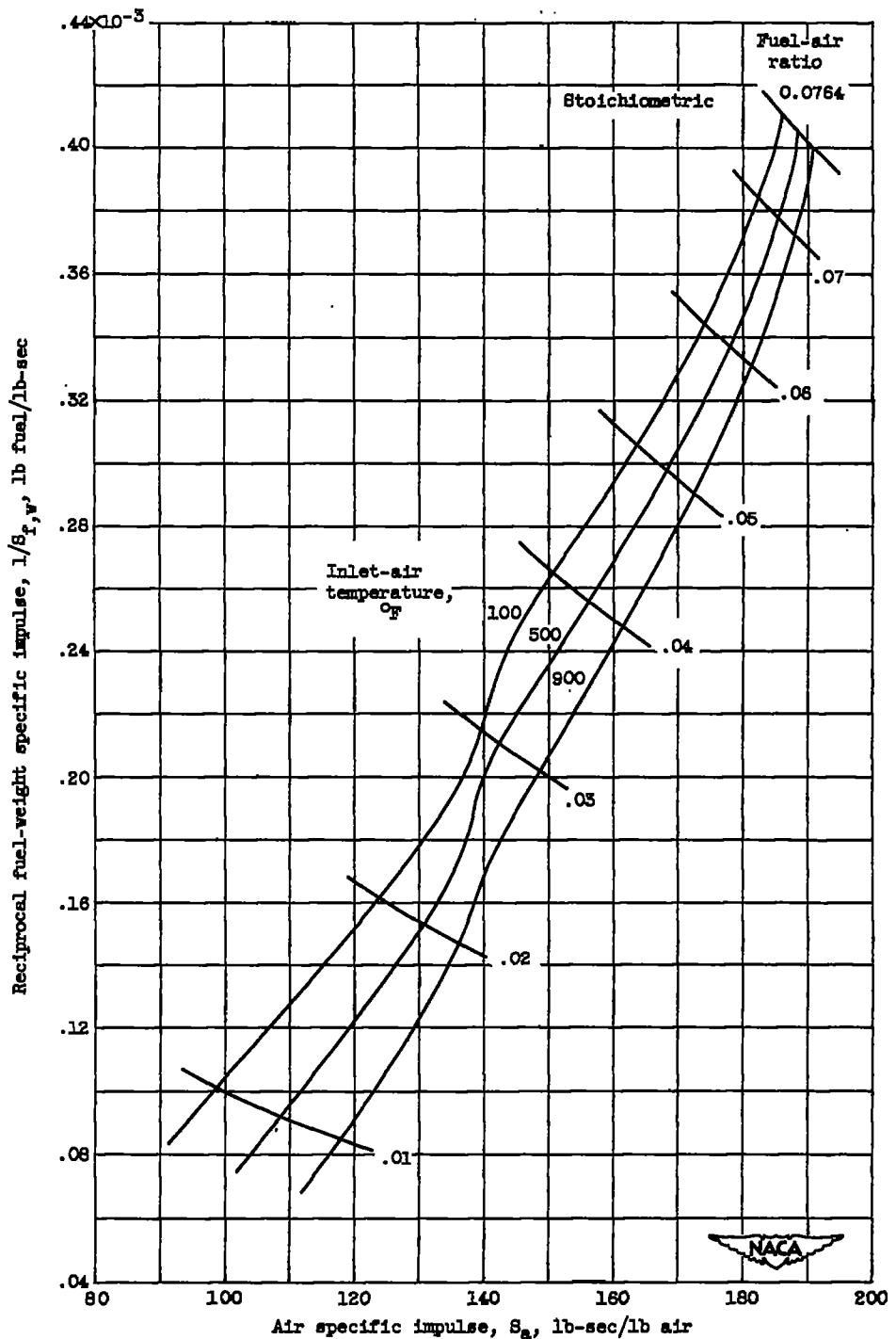


(b) Variation of air specific impulse with inlet-air temperature and equivalence ratio. Combustion pressure, 2 atmospheres.

Figure 5. - Continued. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of liquid pentaborane.

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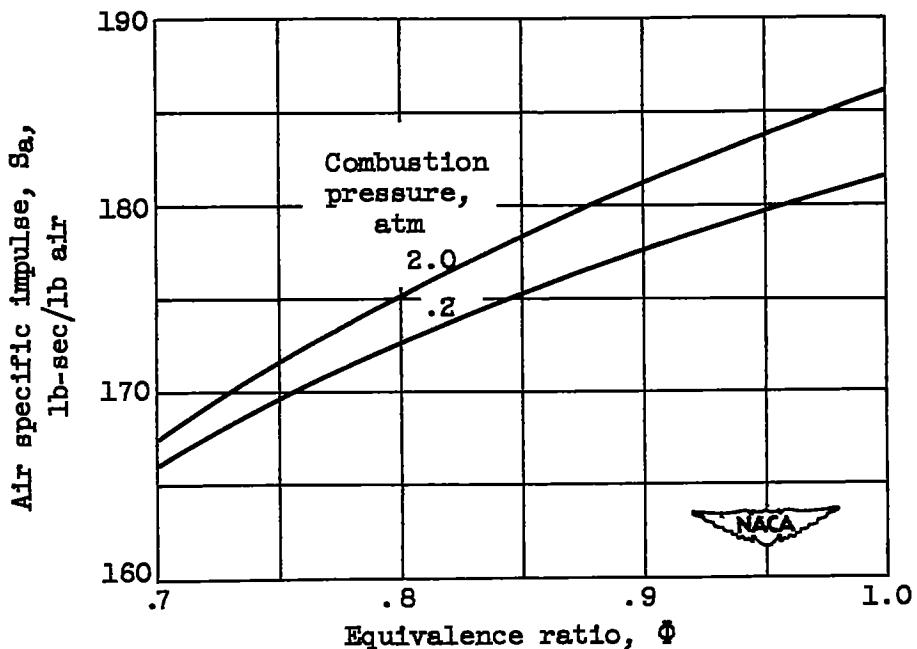


(c) Variation of reciprocal fuel-weight specific impulse with air specific impulse and inlet-air temperature. Combustion pressure, 2 atmospheres.

Figure 5. - Continued. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of liquid pentaborane.

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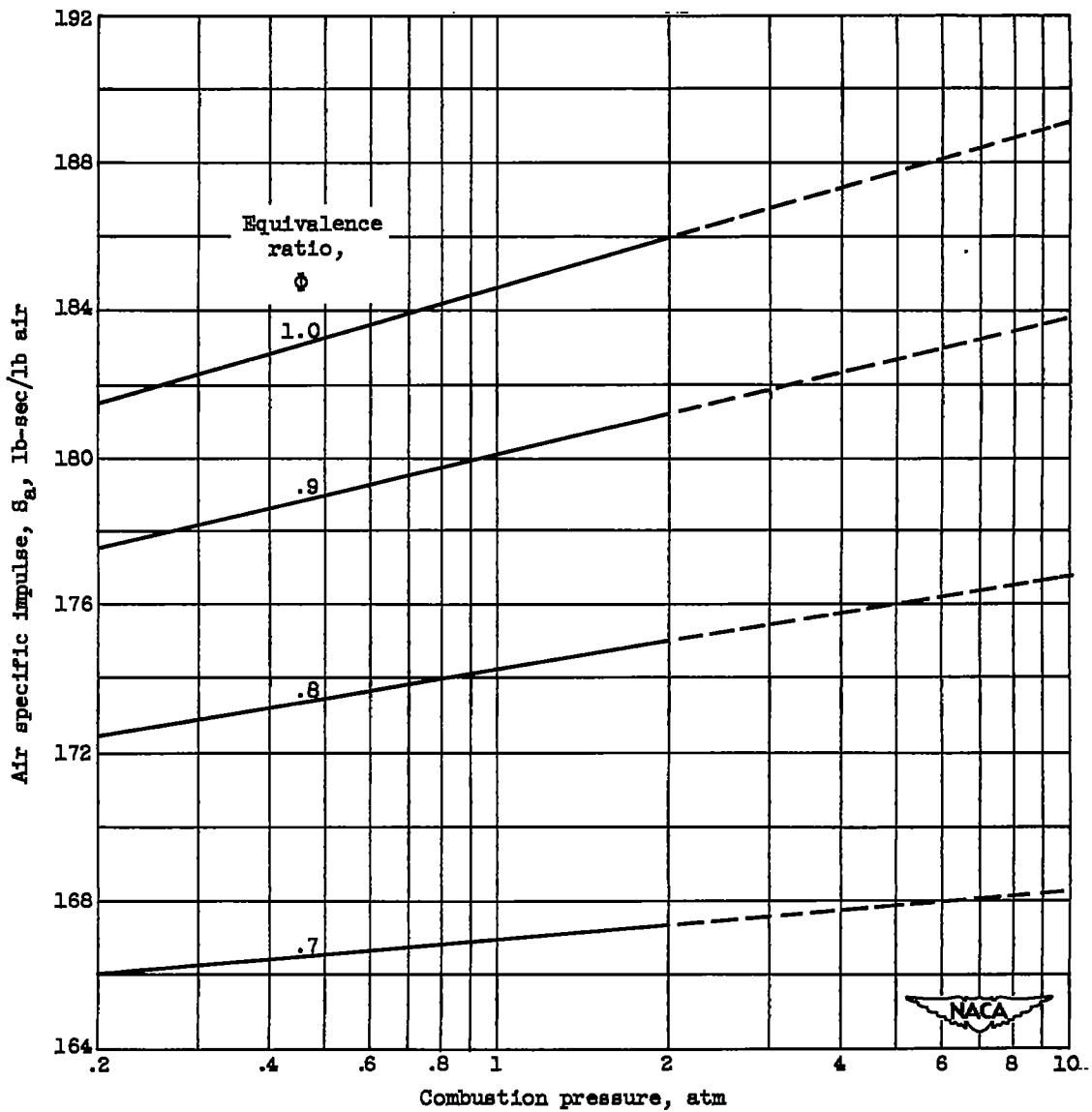
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(d) Variation of air specific impulse with combustion pressure and equivalence ratio. Inlet-air temperature, 100° F.

Figure 5. - Continued. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of liquid pentaborane.

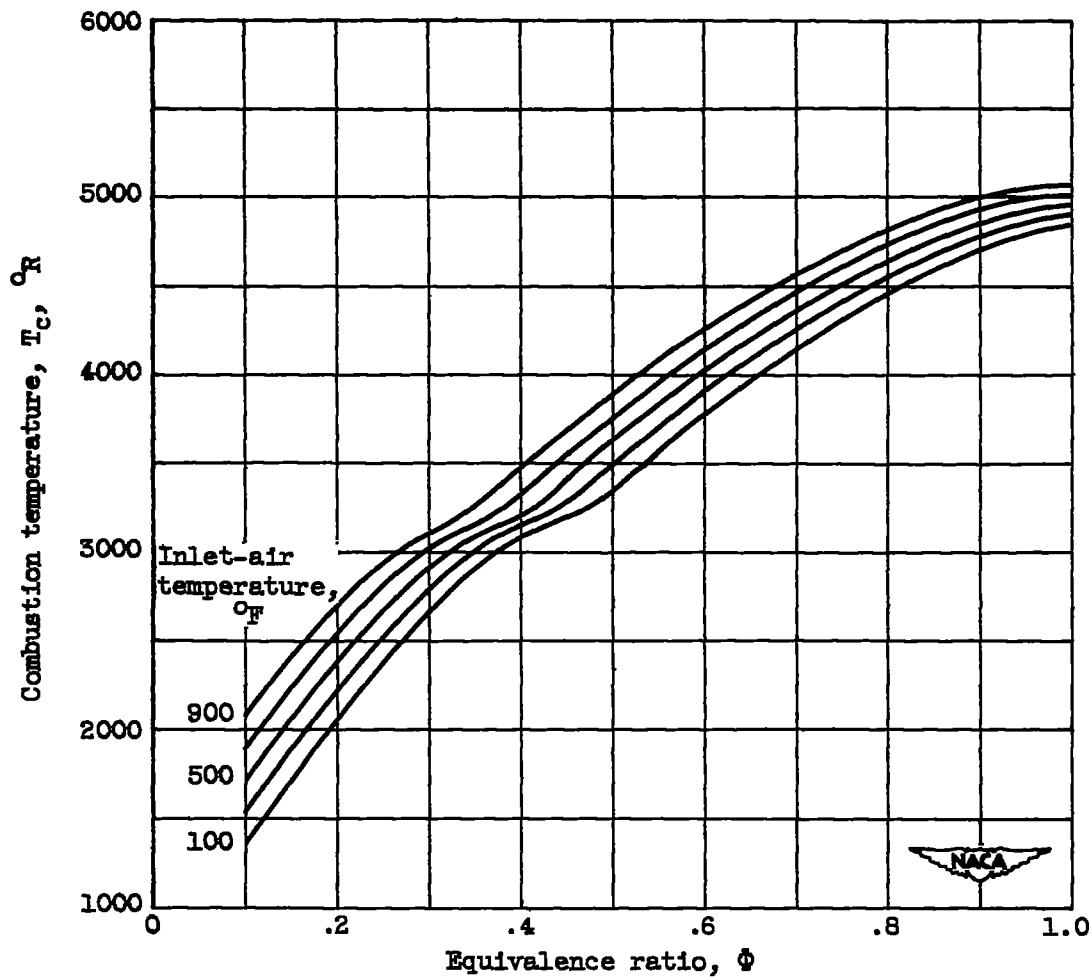
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(e) Variation of air specific impulse with combustion pressure at selected equivalence ratios. Inlet-air temperature, 100° F.

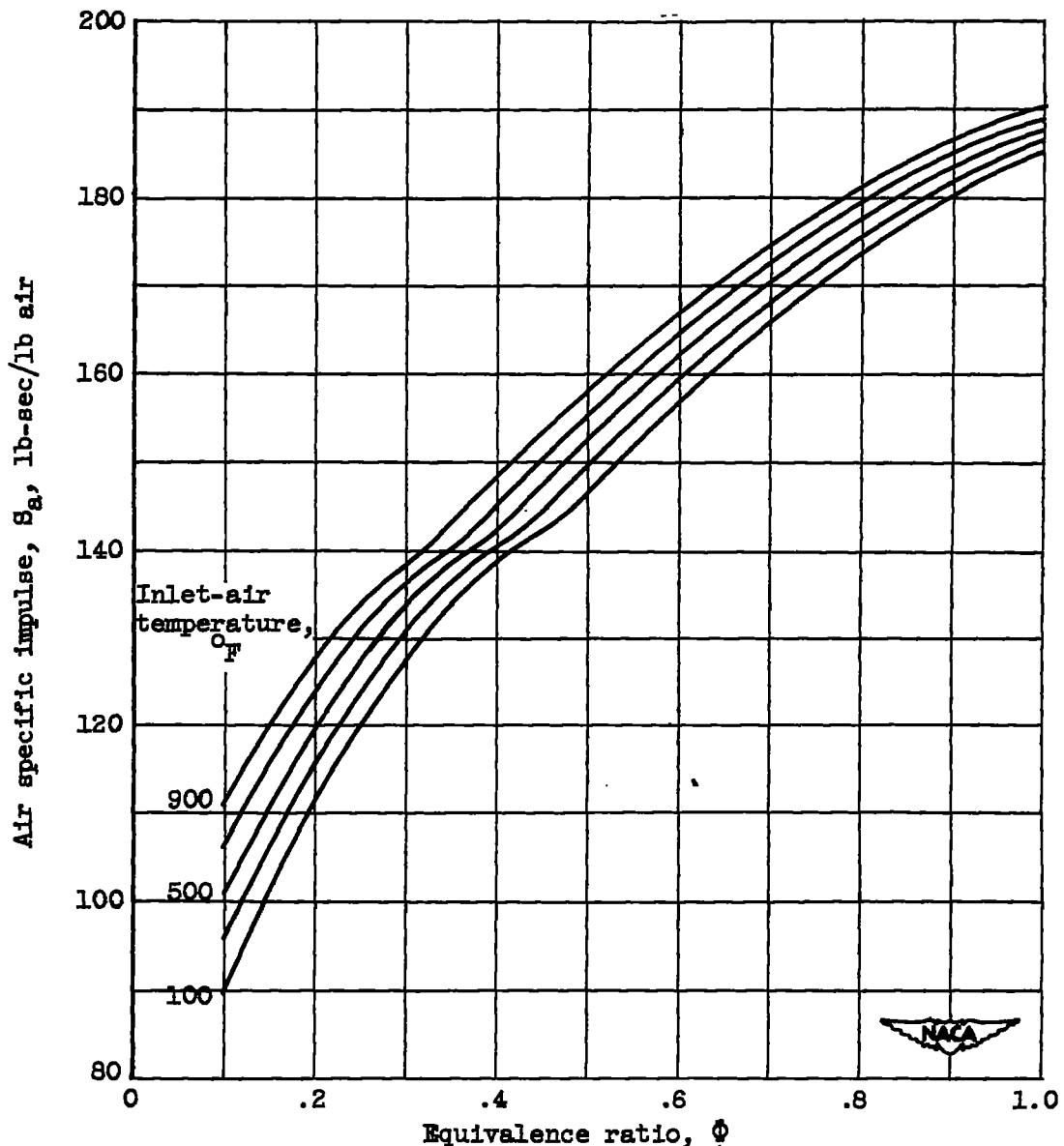
Figure 5. - Concluded. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of liquid pentaborane.

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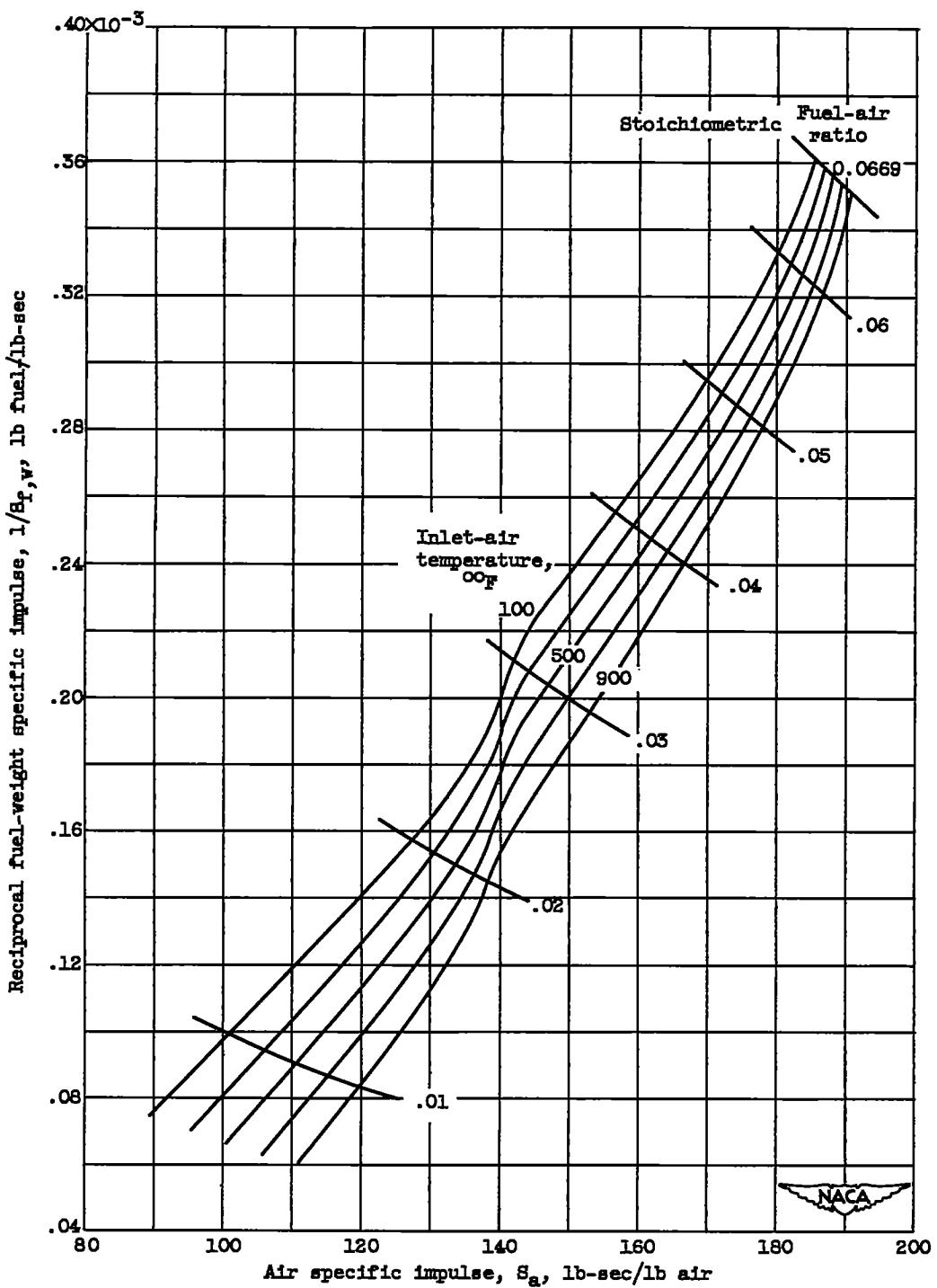
(a) Variation of combustion temperature with equivalence ratio and inlet-air temperature. Combustion pressure, 2 atmospheres.

Figure 6. - Effect of ram-jet combustor inlet conditions on theoretical combustion performance of liquid diborane.



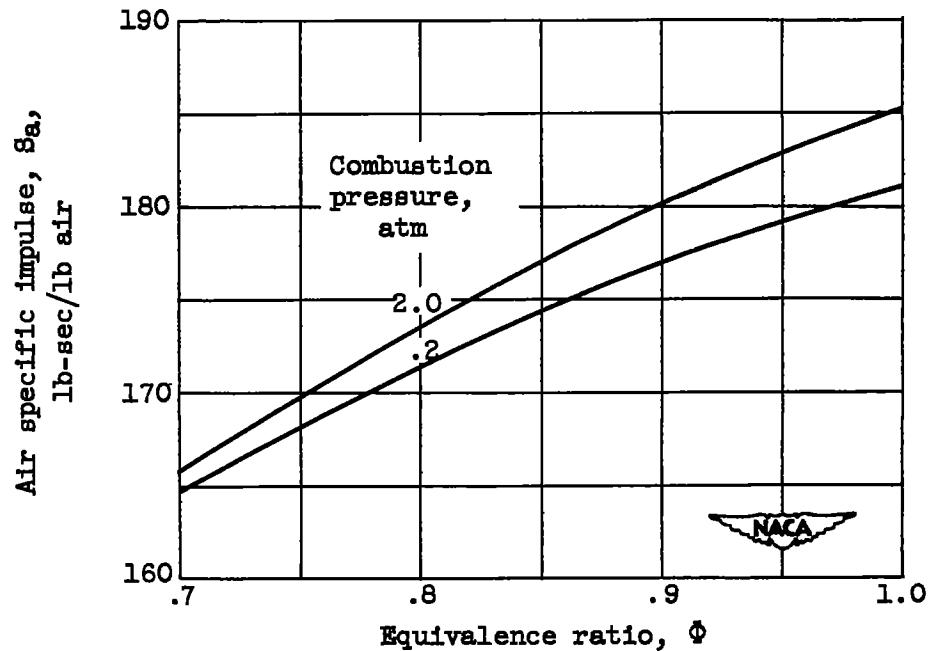
(b) Variation of air specific impulse with inlet-air temperature and equivalence ratio. Combustion pressure, 2 atmospheres.

Figure 6. - Continued. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of liquid diborane.



(c) Variation of reciprocal fuel-weight specific impulse with air specific impulse and inlet-air temperature. Combustion pressure, 2 atmospheres.

Figure 6. - Continued. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of liquid diborane.

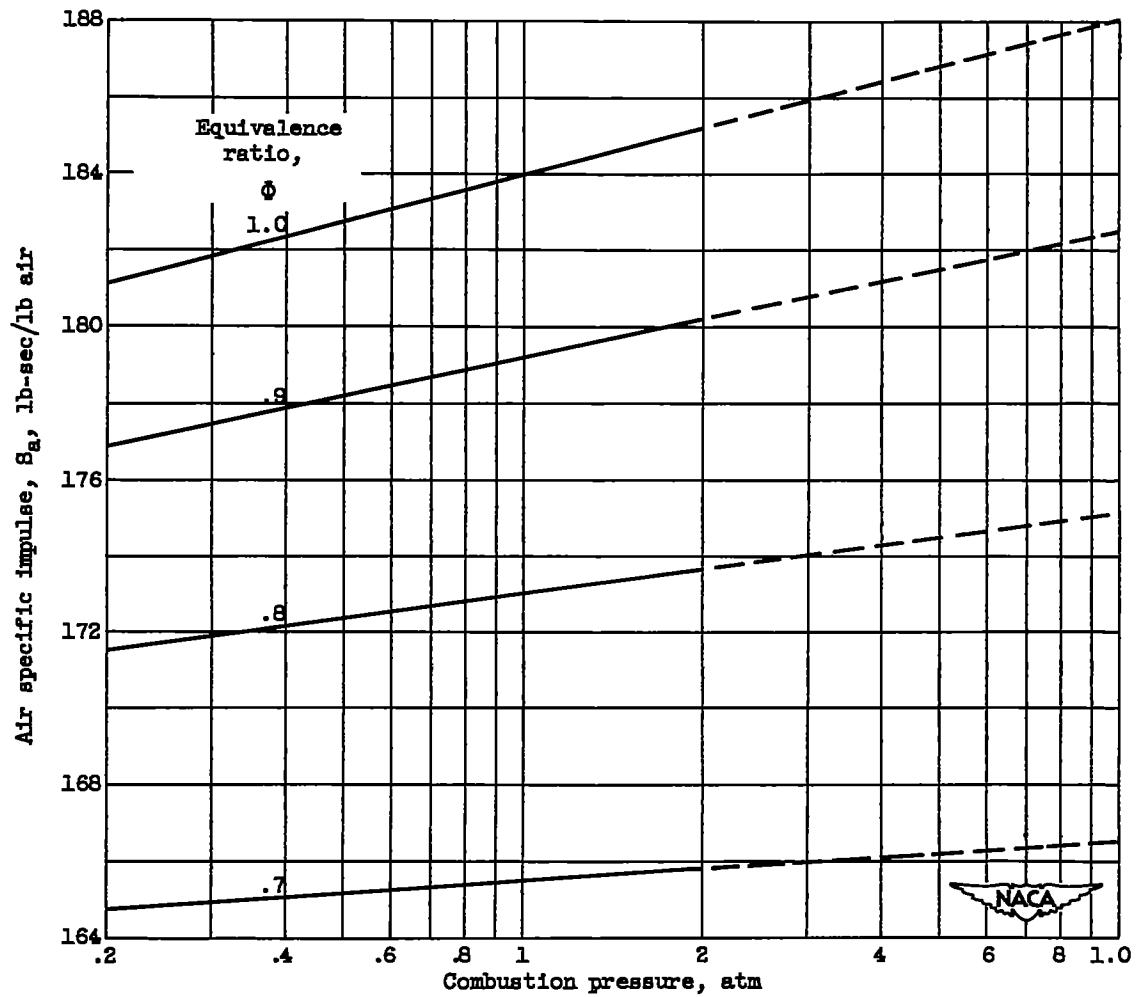


(d) Variation of air specific impulse with combustion pressure and equivalence ratio.
Inlet-air temperature, 100° F.

Figure 6. - Continued. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of liquid diborane.

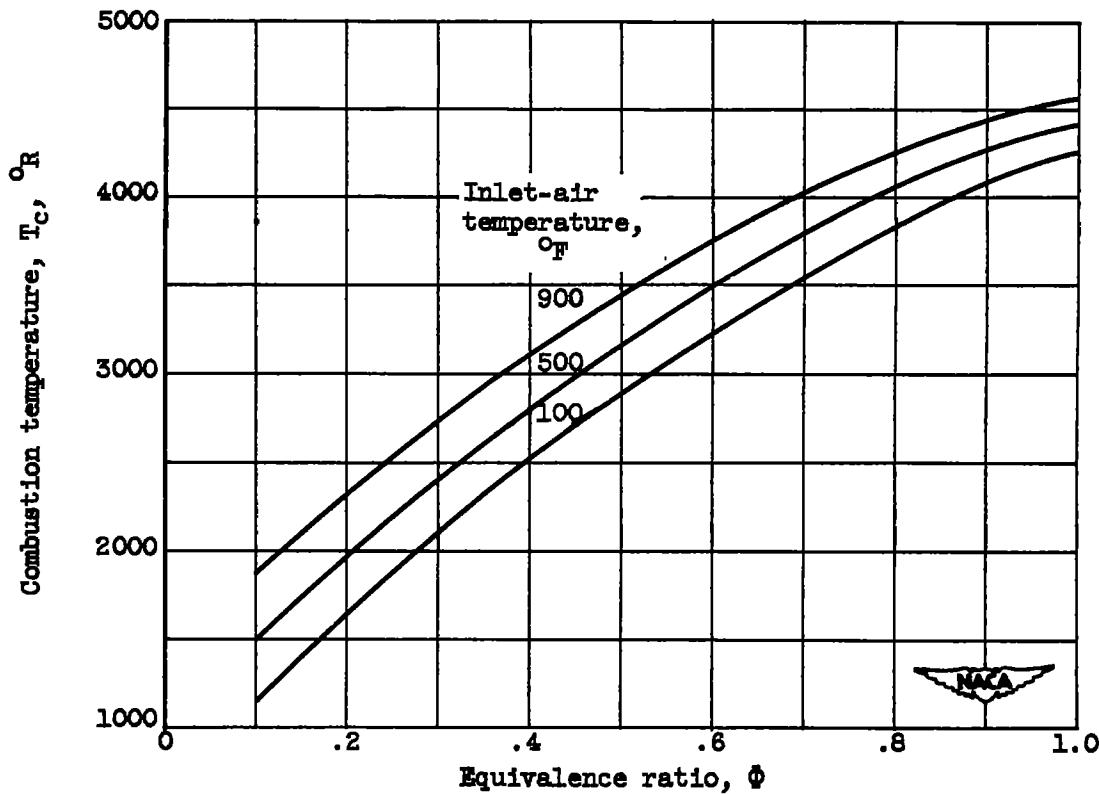
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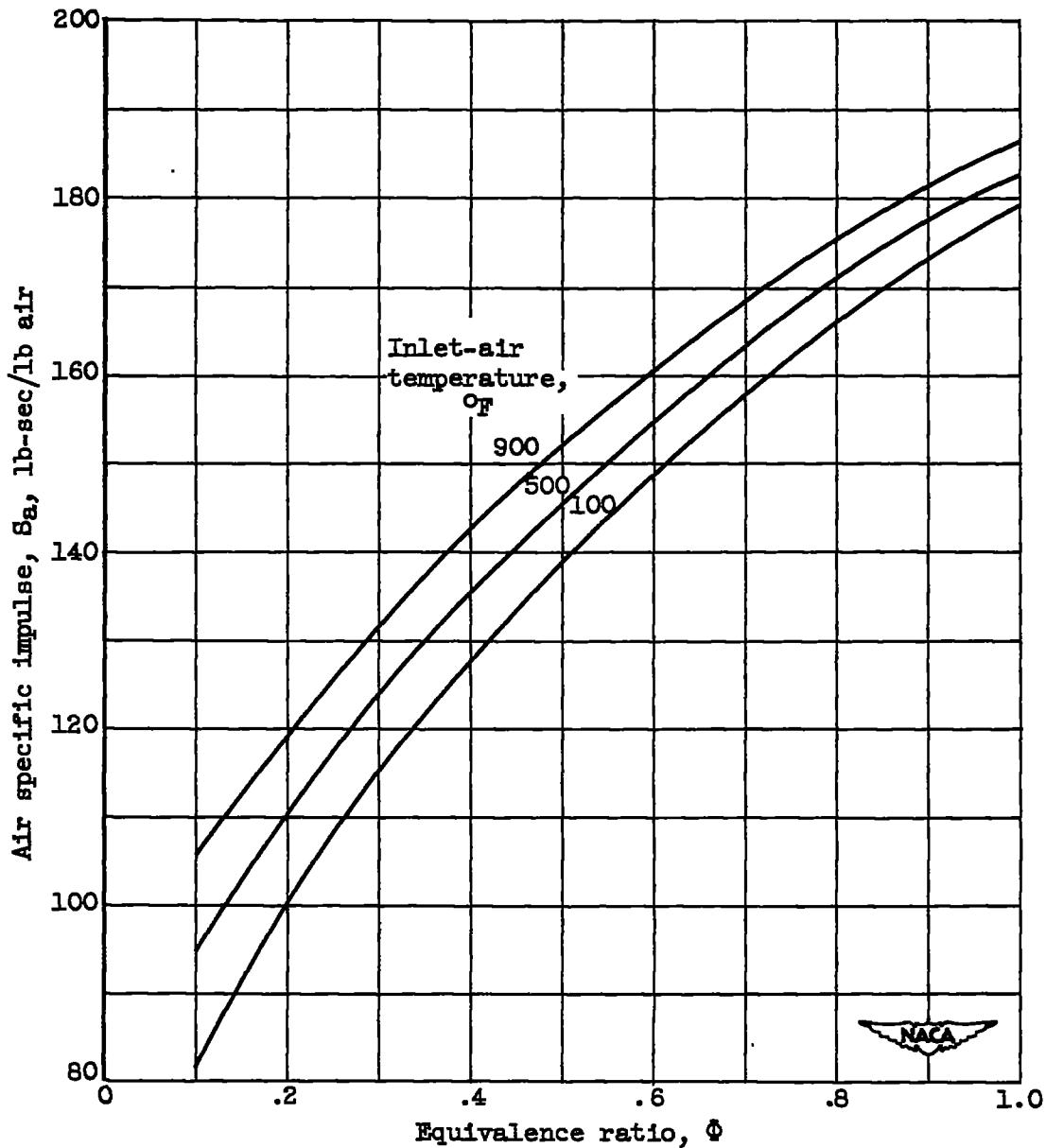
(e) Variation of air specific impulse with combustion pressure at selected equivalence ratios. Inlet-air temperature, 100° F.

Figure 6. - Concluded. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of liquid diborane.



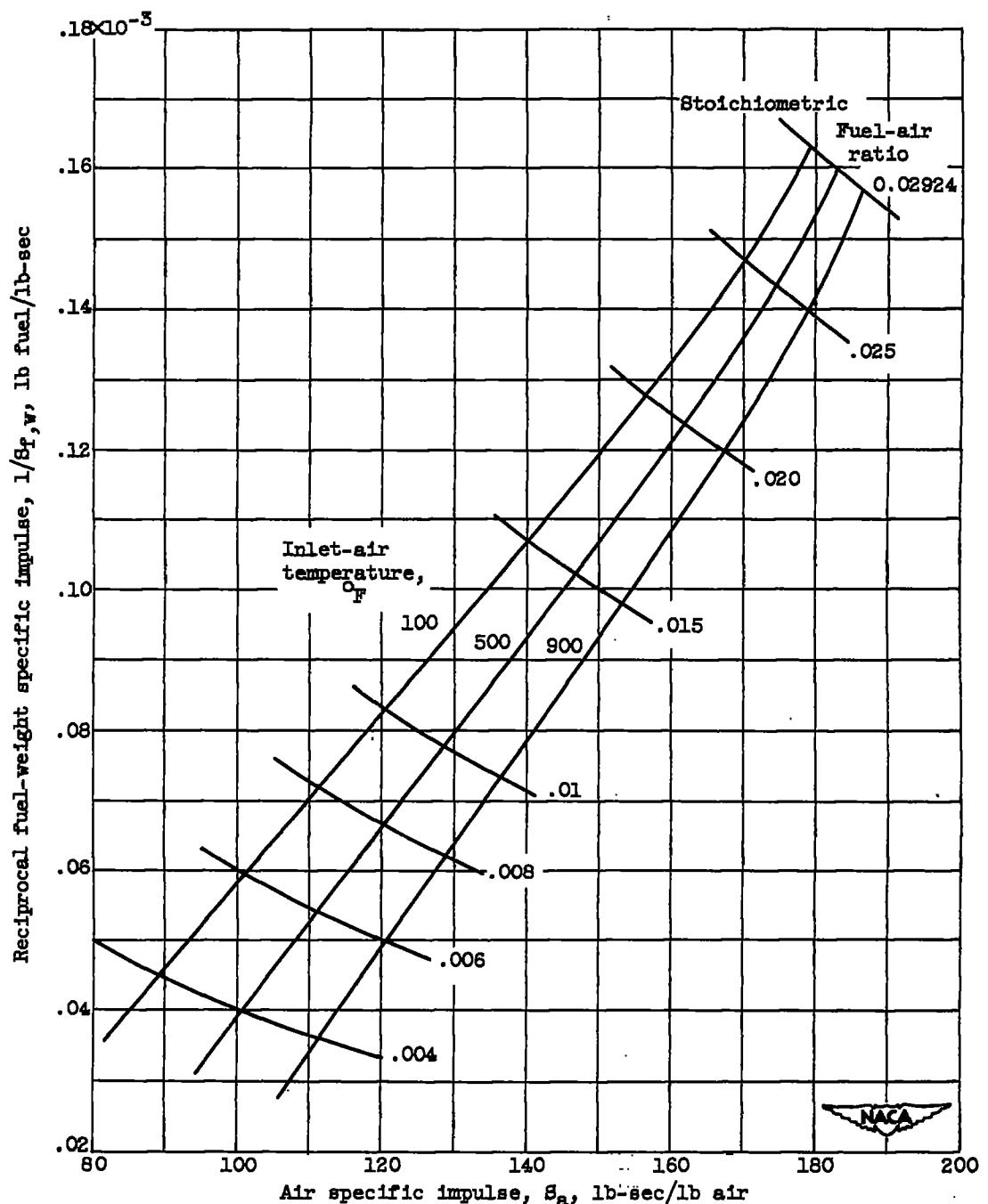
(a) Variation of combustion temperature with equivalence ratio and inlet-air temperature. Combustion pressure, 2 atmospheres.

Figure 7. - Effect of ram-jet combustor inlet conditions on theoretical combustion performance of liquid hydrogen.



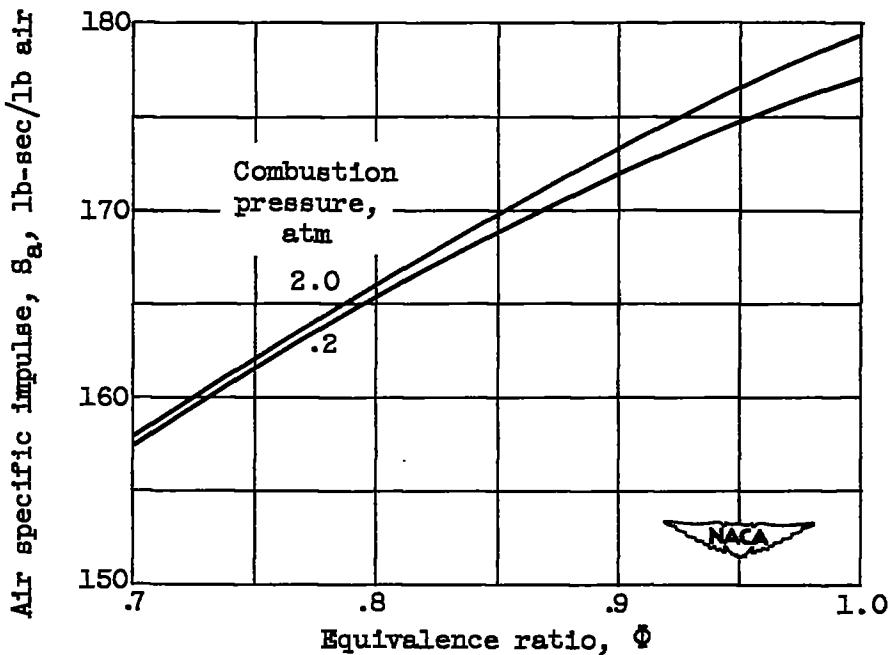
(b) Variation of air specific impulse with inlet-air temperature and equivalence ratio. Combustion pressure, 2 atmospheres.

Figure 7. - Continued. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of liquid hydrogen.



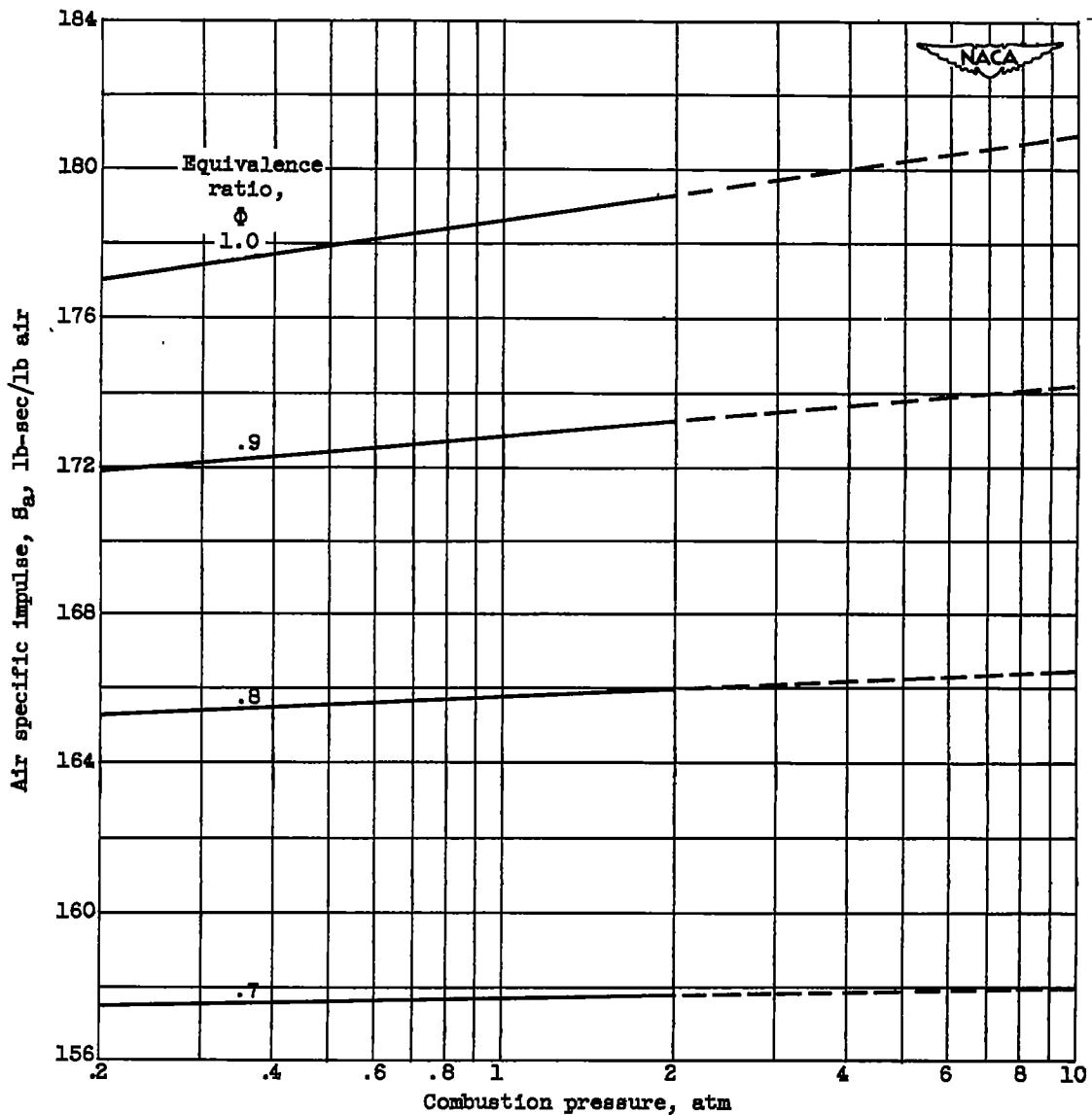
(c) Variation of reciprocal fuel-weight specific impulse with air specific impulse and inlet-air temperature. Combustion pressure, 2 atmospheres.

Figure 7. - Continued. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of liquid hydrogen.



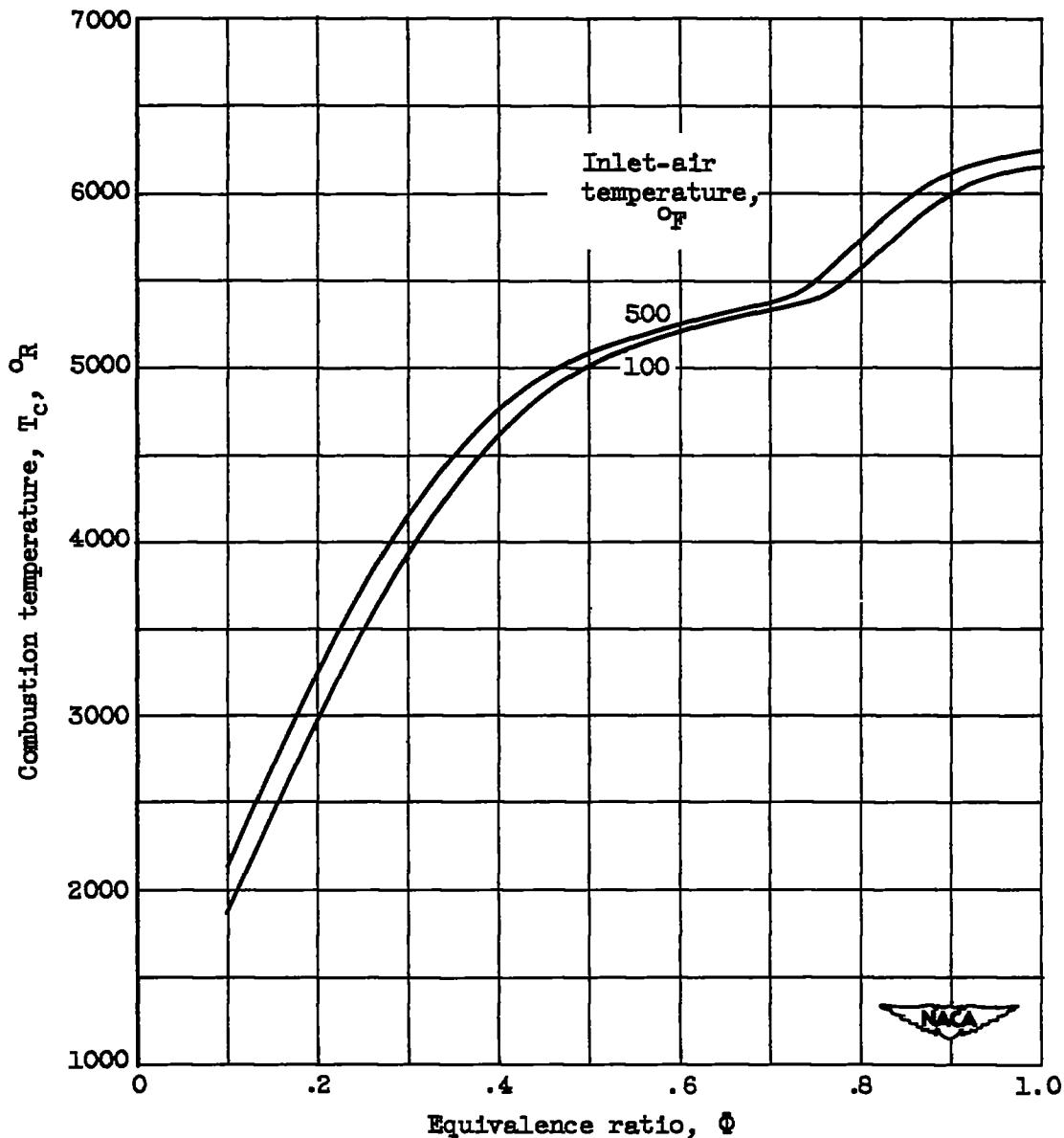
(d) Variation of air specific impulse with combustion pressure and equivalence ratio. Inlet-air temperature, 100° F.

Figure 7. - Continued. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of liquid hydrogen.



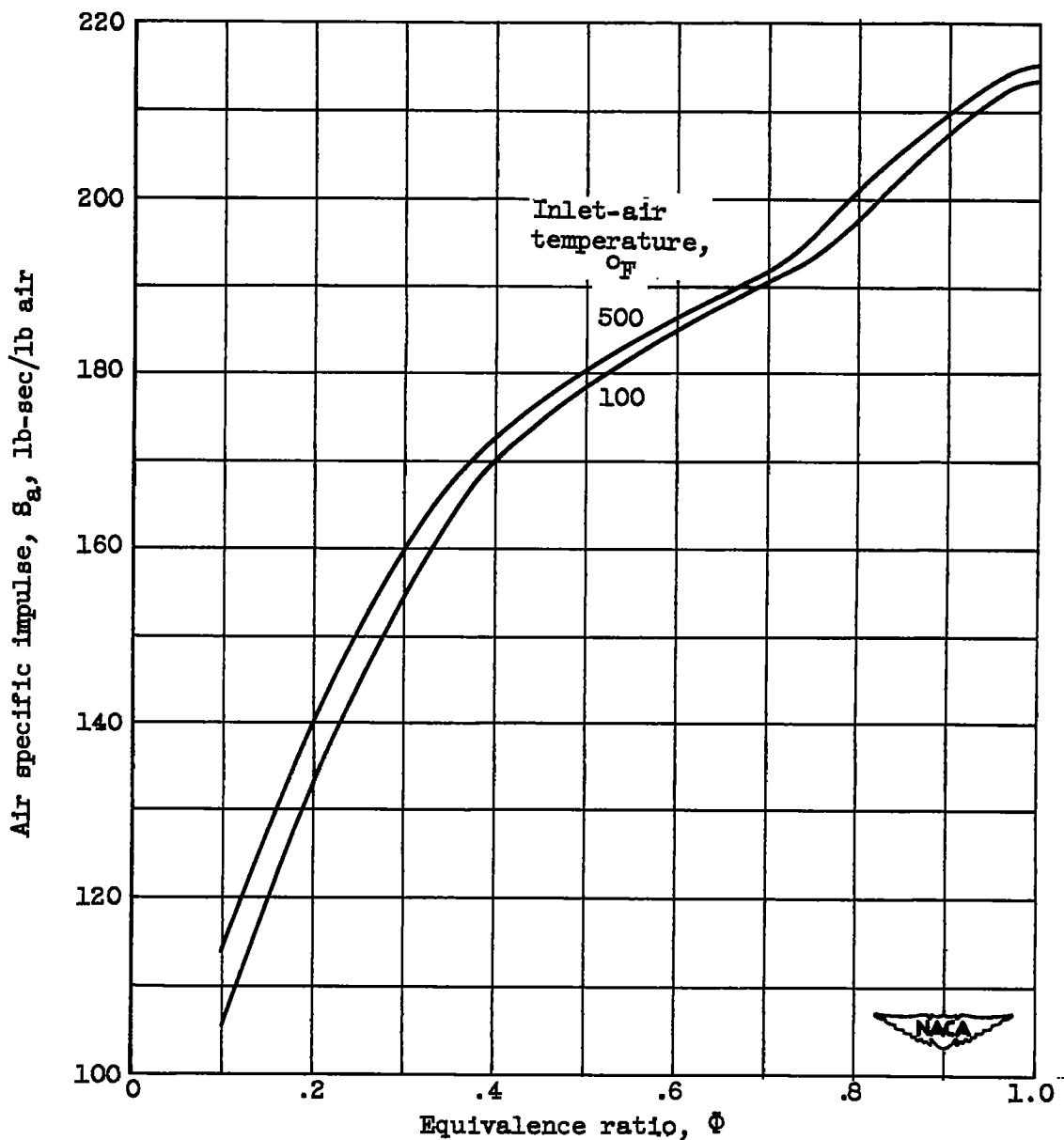
(e) Variation of air specific impulse with combustion pressure at selected equivalence ratios. Inlet-air temperature, 100° F.

Figure 7. - Concluded. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of liquid hydrogen.



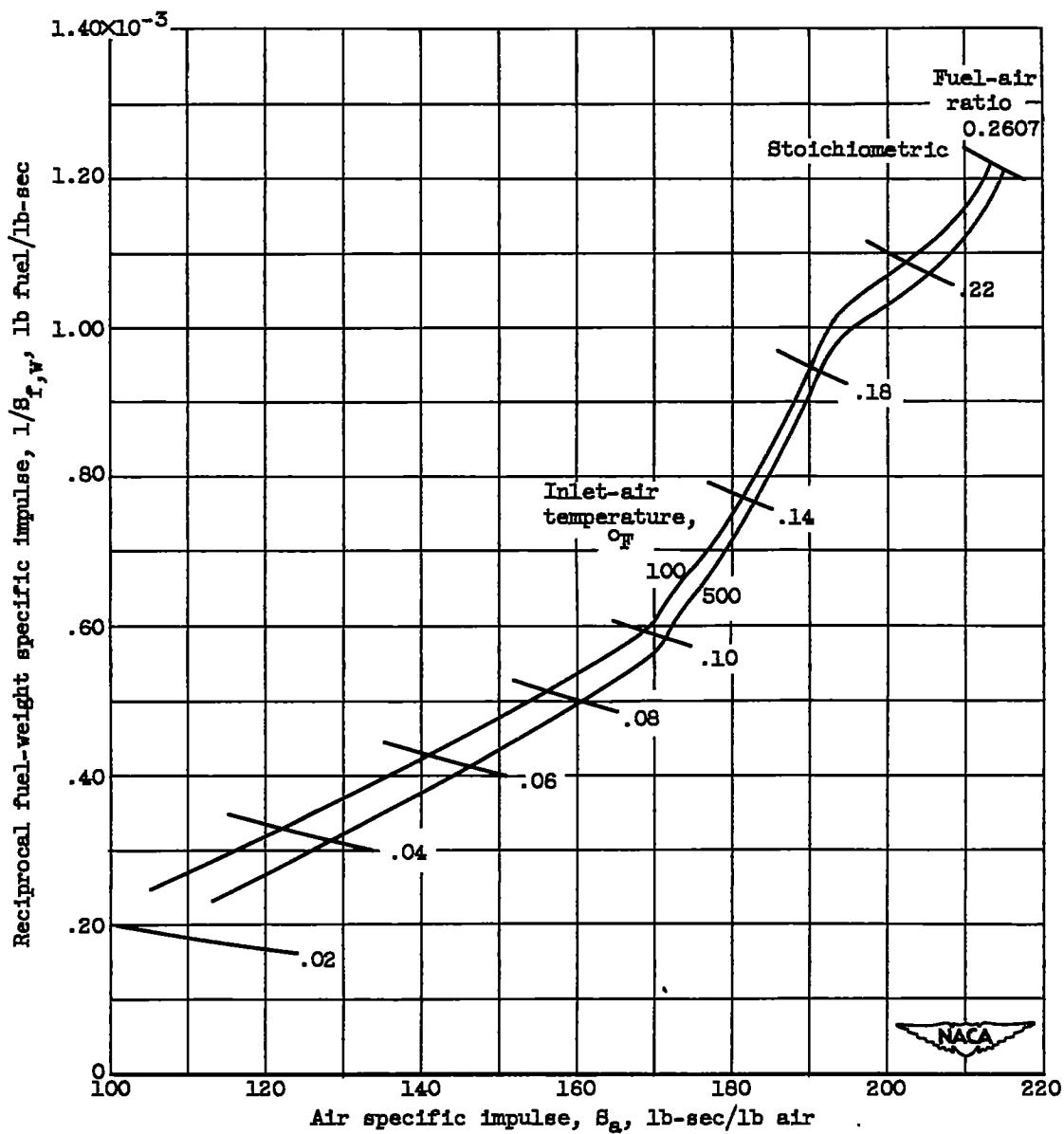
(a) Variation of combustion temperature with equivalence ratio and inlet-air temperature. Combustion pressure, 2 atmospheres.

Figure 8. - Effect of ram-jet combustor inlet conditions on theoretical combustion performance of crystalline aluminum.



(b) Variation of air specific impulse with inlet-air temperature and equivalence ratio.. Combustion pressure, 2 atmospheres.

Figure 8. - Continued. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of crystalline aluminum.



(c) Variation of reciprocal fuel-weight specific impulse with air specific impulse and inlet-air temperature. Combustion pressure, 2 atmospheres.

Figure 8. - Concluded. Effect of ram-jet combustor inlet conditions on theoretical combustion performance of crystalline aluminum.

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